INSULATING THERMAL WINDOW SHUTTERS FOR A MEDITERRANEAN CLIMATE

by

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Abstract

This is a study on energy savings by applying and controlling thermal window shutters in a Mediterranean climate. The study starts with a historical flashback on windows in architecture. After examining the factors that affect their thermal performance, technologies and applications aiming to its improvement will be presented.

The dissertation then proceeds to the experimental part of the study. This has a simulation part and a real case experiment. On the first part two basic structures of south facing thermal shutters are assessed for the Mediterranean climate: the planar thermal shutter and the louvered thermal shutter. Several materials and control strategies are tested. On the second part, that is actually supportive of the first part, different shutters' control strategies are tested in a real case residential building on the south of Greece.

The best construction was proved to be the aluminium insulating louvered shutters that gave a final total energy load reduction of **23.5%.** The results were impressive for the cooling load reduction that was **45%**. The max profitable investment for these shutters would be **81.0 €/m²** (£ 55.0).
However the simple wooden shutters also gave a satisfactory load reduction of **14%** where **33.5 %** was due to cooling load. The max profitable investment for these shutters would now be **38.5 €/m²** (£ 26.12).
Parameters are then examined that influence loads and profits as window-to-floor ratio, orientation and glazing type. East and west windows shutters were proved a much more profitable investment whereas only single glazing gave a satisfying payback period.
The real case experiment showed that when shutters were used during the day the interior temperature was reduced roughly by 2°C when temperatures picked in the mid-day. When applying aluminium foil on the same shutters the results showed that the temperature was further reduced.

Introduction

Aims of study

Windows are unique building elements for providing outdoor views and natural lighting and also considerable amounts of solar energy in the house. However, windows may also lose great amounts of heat compared to heat lost from walls and ceilings or cause overheating.

'In a typical house in the northern half of the United States about 15 to 35% of the total heat-loss in winter is via the windows. [...][1] In northern climates, heat losses via windows are even larger. Yannas (1994) reports that if the highest allowable glazing to floor area - according to British Building Regulations of 1990- is applied, windows in UK will account for 50% of total envelope heat loss.[2] Heat-loss through double-glazed windows or in moderate climates is not as serious. However in such climates there is a bigger likelihood of windows to produce overheat.

The objective of this study is to investigate the possibility of energy savings by using external thermal shutters in a Mediterranean climate. Which structure and control strategy result in high energy savings? What other parameters are crucial when applying thermal shutters on windows?

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[1] *In passively solar-heated houses the percentage of heat loss via the windows is greater – about 20 to 40%- because such houses have especially large window areas.' (Shurcliff, 1980).*

[2] *Byberg M.R. et al., (1985) states something similar: in Denmark 'about 35-50% of the total heat loss occurs through the windows.'*

The definition of the term: thermal shutter

The way the word 'shutter' is used in this dissertation is the way the word is interpreted etymologically. A 'thermal shutter' is perceived as a device able to occlude and found at the verge of two different environments –in our case the exterior and the interior space of a building. With the presence or absence of its attributes it affects the thermal conditions of the space that needs to be controlled. In everyday speech a shutter represents 'a rigid insulating plate, or set of rigid plates or rigid strips, used to cover a window'.

The shutter has in any case a dynamic sense. The shutter is placed behind or in front of a susceptible building element, such as a window or door. Therefore the function of a shutter should always be examined in relation with glass. It is the dual function of those two elements that is important.

At the introduction of the study I will tempt to present briefly the evolution of windows and glass and the trends in current building construction.

The evolution of glass in window design

Historical flashback

'One could say that the history of windows is the same as that of architecture or , at least, this is the trait which is the most characteristic in the history of architecture'. (Le Corbusier, cited Olgyay A. and Olgyay V., 1957)

'Primitive dwellings were provided with openings for access. Whether they were constructed of mud, animal hide or sticks, an opening was necessary.' 'These dwellings were mainly for shelter and for rest at night, and windows were not really necessary.' (Lim, et al., 1979).

When people started to stay longer inside their dwellings as agricultural settlement replaced the nomadic lifestyle, windows started becoming indispensable. A closer observation of historical architectural examples would prove that the form and expansion of windows ultimately depends upon climate and lifestyle.

At Egyptian architecture the windows in temples were few. The lack of openings was mainly due to the hot dry climate were massive walls of mud bricks or stone were used to provide the necessary thermal mass and insulation for thermal overheat protection.

Figure 1 : Indian tipi dwelling
Photo by Grabill, John, 1891. Available from:
<http//www.old-picture.com/indian-dwellings-index-001.htm> [Assessed on 12/08/07]

Figure 2 : Temple of Isis at the complex of Philae, Egypt 4th century b.c.
Available from:<http://mangalorean.com/circle/browsearticles.php?arttype=Travelogue&articleid=995> [Assessed on 11/08/2007]

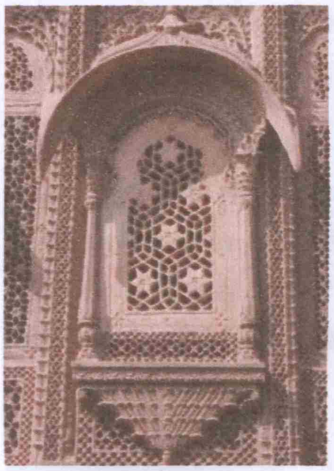

Figure 3 : Lattice Indian window.
Available from:< http://www.grassroots.net.nz/destinations/north_india /main.htm> [Assessed on 11/08/2007]
Figure 4 : Muryangsujon hall of Pusok Temple, Andong, South Korea, 13th century.
Available from:< http://www.britannica.com/ebc/art-2849/Muryangsujon-hall-of-Pusok-Temple-Andong-South-Korea-wood-13th> *[Assessed on 11/08/2007]*

"In the Indian sub-continent architecture 'pierced, or latticed, windows were common to exclude sunlight and heat and to provide essential ventilation for this hot humid climate. In Chinese Architecture 'fenestration took a more important role in the design of ancient Chinese buildings.' 'The buildings were basically of column-and-beam wooden constructions and 'window walls' were constructed between the structural members.' 'Often rice-paper was used to afford privacy.' 'Windows and doors were generally protected by eaves, and their curved outlines became the characteristic feature of Chinese architecture.' (Lim et al., 1979)

Although the glass as material was known since ancient times[3] it was not used in common windows. Actually what restricted the expansion of glass in window constructions is that they were not able to make glass panes large enough. The size of openings was also limited because of construction burdens. However, the use of smaller pieces of stained glass was introduced in architecture of religious buildings of Byzantium and later expanded in Gothic architecture. Eventually the technique of glass manufacture developed and by 1240 clear and colorless window glass was available for Westminster Abbey. 'For domestic buildings the windows became more functional. In Britain wooden shutters had

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[3] *Glass manufacturing was common in Egypt at the 18th Dynasty and samples were discovered at Tel el' Amarna. Also " the Romans occasionally used colored glass for making windows(Lim et al., 1979).*

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not yet been completely replaced by glass, and still retained the Norman characteristics.' (Lim et al. 1979, pp.9-10)

In England, Sir William Chambers reckons that 'sash windows are neater and more convenient than casements. Shutters should be inside the building if 'beauty is aimed at' and they are to be of the folding type and to be housed in the body of the wall.'(Chambers, 1791 cited Lim et. al,1979). At the same time the so called 'French windows' that had 'louvered shutters or volets were used.

Figure 5 : Victorian interior and exterior shutters (left) and French style window (right) (Hertzog et all, 2004)

Later in time, the further development of the technology of glass and cast iron made it possible for glass to expand in larger surfaces and curvilinear shapes to form roofs of large span, to cover arcades, markets and gardens. As a result great glass constructions were accomplished such as the Crystal Palace at the mid 19th century and several plant houses. The all-glass look as of Crystal Palace started a certain amount of 'glass-mania'. (Lim et al., 1979 p.17)

'It is during this period that the 'glasshouse' effect was realized if not fully understood. Additional insulation against the winter cold was provided by covering the glass with canvas, and cavity construction in some parts of roofs was used as it enclosed 'a body of air to prevent the escape of heat' (Hix, 1974, p.45). We can already start talking about double skin constructions.

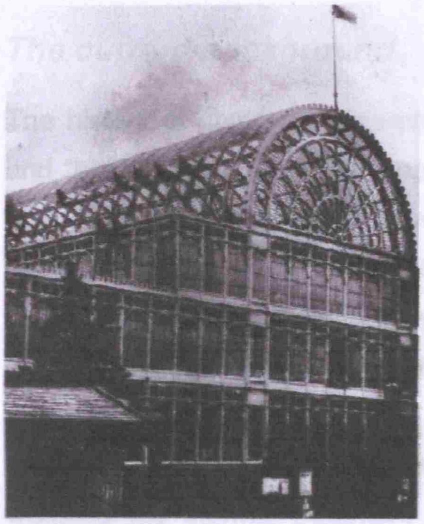


Figure 6 : Crystal Palace
(Available from: <http://www.ric.edu/faculty/rpotter/cryspal.htm> [Assessed on 12/08/07])

The new arrival and proliferation of concrete constructions made it possible at the 20th century to make large windows common. The breakthrough of steel buildings gave a new architectural expression of steel frames with glass infill where glass was integrated as part of the construction. Integral glass walls became popular and the concept of 'curtain walling' also emerged.

'The Bauhaus building at Dessau 1926, influenced by Cubism, had continuous glass curtain flowing around the building without apparent supports. The reinforced concrete structure from which the glass was hung was set behind the glass. The extensive transparency which permitted the interior and exterior to be seen simultaneously, gave the appearance of 'overlapping' of space and time.' (Lim et al. 1979 p.42)

Le Corbusier (1929-34) defined the history of architecture as 'the century's-old struggle for light-the struggle for the window.'

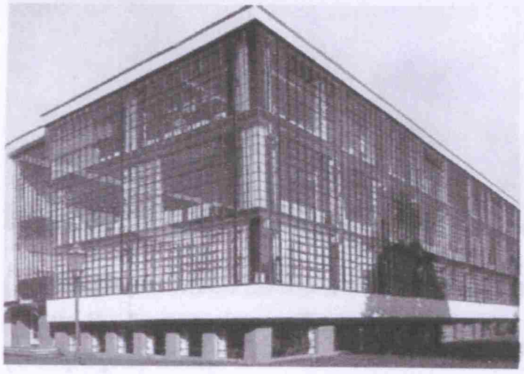


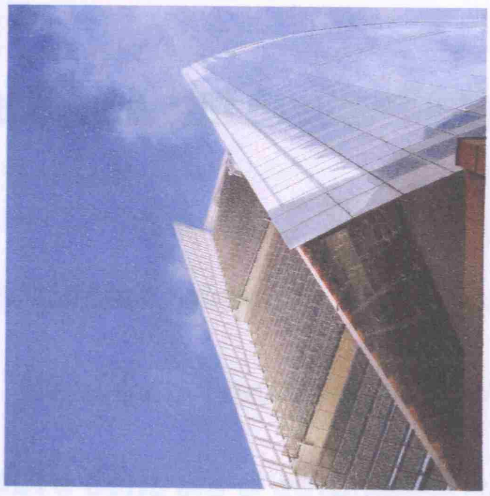
Figure 7 : Bauhaus Building in Dessau, architect:t Walter Gropius.
Available from: <http://www.hubert-brune.de/grafiken/dessau_bauhaus_1925_1926.jpg> [Assessed on 12/08/07]

Figure 8 : Ville Savoy, architect: Le Corbusier 1929.
Available from: <http://www.bc.edu/bc_org/avp/cas/fnart /Corbu/savoye1.jpg> [Assessed on 12/08/07]

The current background

The history of shutters is interrelated with the history and development of glass. Initially and "before sheet glass became commonly available, windows were simple holes in the wall. A shuttering device or cover was used when ventilation and light were not longer needed and thermal comfort was required." When energy was still expensive and glass technology was not developed yet, shutters and curtains played still an important role. However, as energy became widely available and glazing technology improved curtains and window treatments became more decorative than utilitarian. The energy crisis of the '70s with the consensus that energy resources are finite and the later awareness of global warming the thermal treatment of windows became subject for investigation. (Wilson, 1987, p. 26)

Lately much of technological research aiming to improve the windows' performance is focused on progressive glazing. High prestige buildings usually have high percentage of glass on their facades and glass skyscrapers that are the state of the art today, have more of an aesthetic and symbolic role; to express a high-tech profile.



...from simple holes on the wall to whole glass facades, and from local architecture to international.
Figure 9 : Aurora place office and residence, Sydney, 1996-2000, Renzo Piano Build. Workshop. (Compagno, 2002)
Figure 10 : Hoxoviotissa monastery, Amorgos, Greece, 11th century.
Available from: <http://www.brandsborg.com/Jalbum/Cyclades%20-%20AMORGOS%20-%20May%202005/index.html> *[Assessed on 12/08/2007]*

1. Review of Technologies and Applications

Benefits and problems related to windows

Issues on Thermal Comfort

Active controls & automations

Technologies improving window performance

1. Review of Technologies and Applications

First of all the shutter should never be seen alone. To understand the role of it we should first understand the functions of window, review the technologies available for fenestration and the possibility of a shutter to stand alone, replace or in combination together with other techniques.

Benefits and problems related to windows

Main functions of windows

The main functions of the window are to provide daylight and ventilation but nowadays the latter can also be replaced by mechanical ventilation. The effective use of daylight can by reducing reliance to artificial lighting be one of the large single means of energy saving. Apart from that, natural lighting also restores the relation of the humans with the outdoor environment, the awareness of the seasons and the time of the day. Other functions of the windows are to provide views out and to admit solar heat gains that are welcomed during the heated period.

However the benefits related with windows are accompanied by several problems. This study mainly deals with issues related to energy consumption.

Heat losses and solar gains

When solar radiation strikes the surface of a material a proportion is reflected, another is absorbed and some may be transmitted. Unlike opaque building elements glass allows the transmission of light. Sunlight contains no heat but it consists of electromagnetic radiation, both in the visible (0.4-0.7 microns) and in the invisible region (mainly near infrared radiation 0.7- 3 microns) in about equal proportions, whereas objects as those of the interior of buildings emit far infrared (3-80 microns) radiation. Eventually all radiation is absorbed by surfaces that it is then converted into heat. Because of the fact that these near and far infrared spectra are separate without significant overlap and the fact transmission of glass is higher for far infrared wavelength, consequently heat is trapped behind the glass.

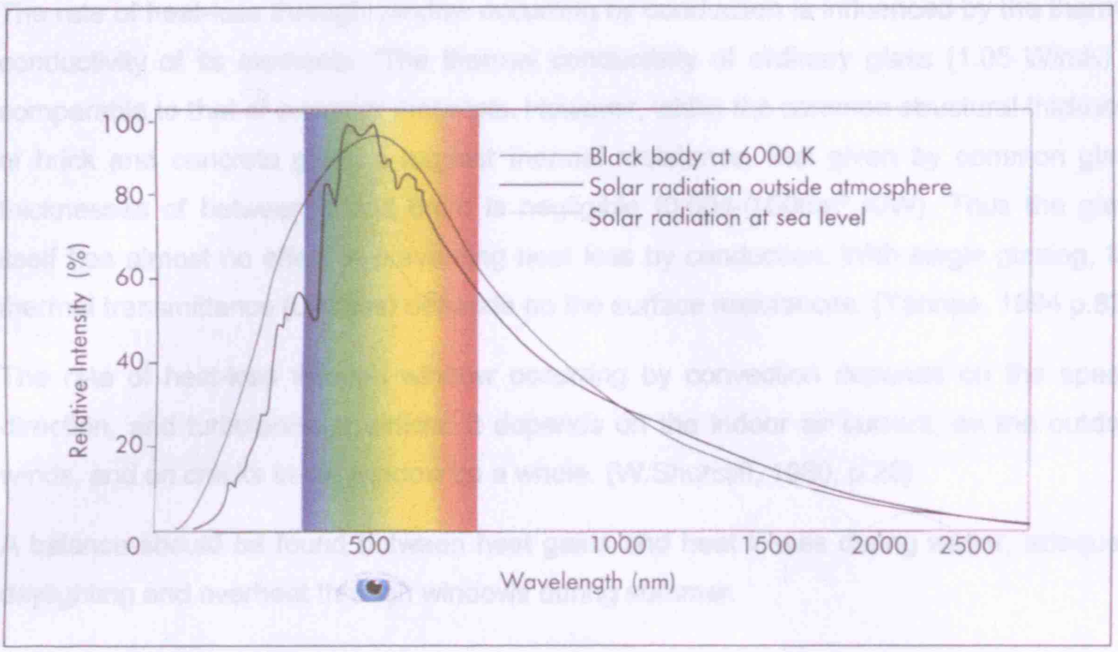


Figure 11 : Spectral graph of solar energy
(Button and Pye, 1993; fig 3.4, p.38]

This phenomenon results in solar heat gains at the interior of the building that are beneficial for winter period but unwelcome during summer because they can cause overheat.

Direct solar gains may be overcome by heat losses. Hestnes, et all, (2003), reports that 'Unfortunately, in the colder north-latitude climates, window losses are greater than solar gains (taken over the whole heating season) for any type of currently available glazing. But in the range of U-values below 0.8 W/m²K, windows are close to neutral.'[4]

As with all building elements heat losses through windows occur by conduction across the material and at its boundary surfaces through radiation and convection. For windows energy flows along many different paths, e.g., through the glass panes, through the mullions and frames of the sashes, and through the fixed frame of the window as a whole Much energy may also be lost by out-leak of room air or by in-leak of cold outdoor air through cracks.

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[4] The ratio of heat loss through window to the total heat loss is relative: "In a house that has a modest area of windows heat-loss through windows looms large if the windows are single glazed but not if they are double glazed. (30% vs. 17%) Heat-loss through double-glazed windows is not serious in houses in moderate climates unless the aggregate area of windows is large.' (Shurcliff, 1980, p.24)

The rate of heat-loss through window occurring by conduction is influenced by the thermal conductivity of its elements. 'The thermal conductivity of ordinary glass (1.05 W/mK) is comparable to that of masonry materials. However, whilst the common structural thickness of brick and concrete gives a modest thermal resistance, that given by common glass thicknesses of between 4 and 6mm is negligible (0.004-0.006m² K/W). Thus the glass itself has almost no effect in preventing heat loss by conduction. With single glazing, the thermal transmittance (U-value) depends on the surface resistances. (Yannas, 1994 p.82)

The rate of heat-loss through window occurring by convection depends on the speed, direction, and turbulence of airflow. It depends on the indoor air current, on the outdoor winds, and on cracks in the window as a whole. (W.Shurcliff, 1980, p.20)

A balance should be found between heat gains and heat losses during winter, adequate daylighting and overheat through windows during summer.

Summer overheat

Excess solar radiation transmitted through windows can cause overheat during summer period. However, interiors should be naturally lit to meet the illumination demands. 'Obviously for lighting we are interested only in the visible part of the spectrum, but this still carries half the energy that potentially can become heat.' (Baker and Steemers, 2002) It is critical that a balance be met so that the amount of daylight is adequate at the interior but any excess could rise cooling load.

Latitude and weather, sunshine frequency, orientation and slope of the window are factors that primarily influence the risk of overheat. 'Over the whole year south-facing vertical surfaces receive more than twice as much radiation as surfaces facing north.' (Yannas, 1994). At Figure 12, Figure 13 and Figure 14 solar radiation incident on north, south and west facing vertical surface throughout the year is shown.

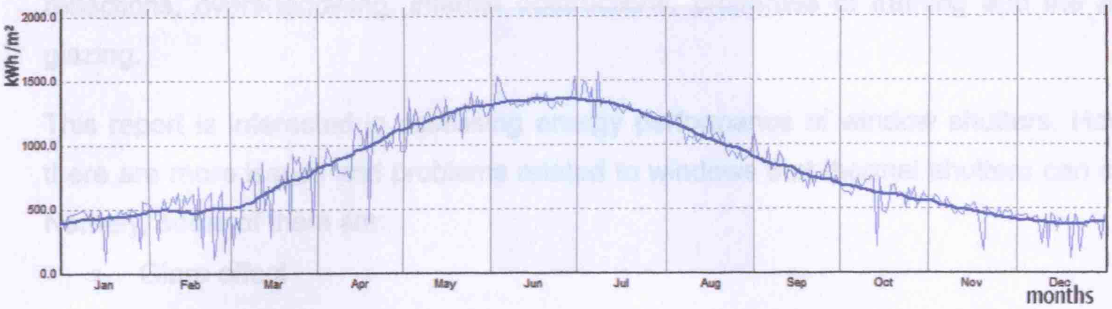

Figure 12 : Annual incident solar radiation on a north facing vertical surface in Greece. Total annual collection 298 kWh/m², whereas in London 202 kWh/m². [Source: Square one software]

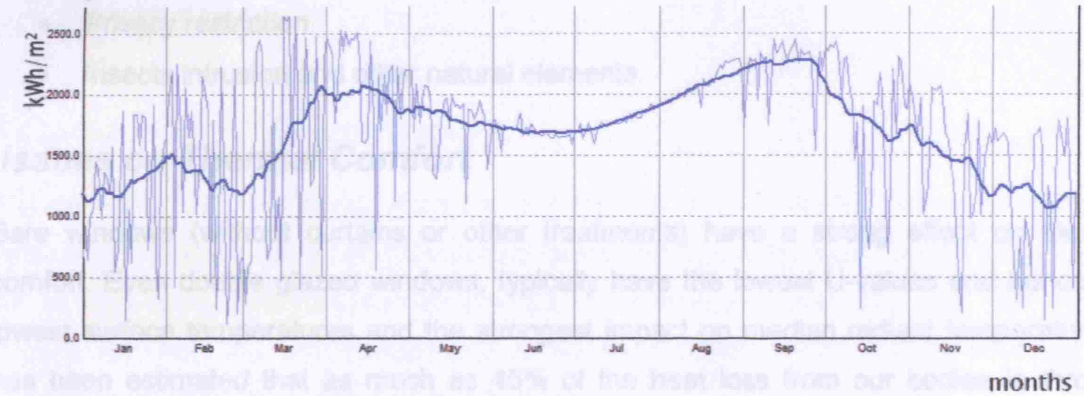

Figure 13 : Annual incident solar radiation on a south facing vertical surface in Greece. Total annual collection 619 k Wh/m², whereas in London 395 kWh/m². [Source: Square one software]

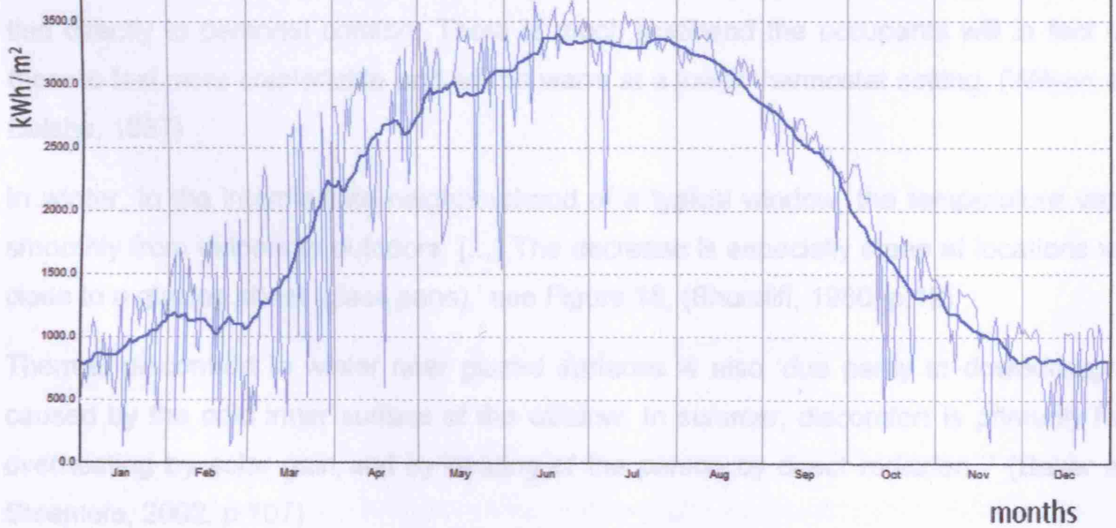

Figure 14 : Annual incident solar radiation on a western facing vertical surface in Greece. Total annual collection 758 k Wh/m², whereas in London 329 kWh/m². [Source: Square one software]

Other factors that may affect the amount of solar gain through windows are: external reflections, overshadowing, internal obstructions, properties of framing and the area of glazing.

This report is interested in assessing energy performance of window shutters. However, there are more issues and problems related to windows that thermal shutters can control. Namely, some of them are:

- Glare effect
- Sound and Noise penetration
- Condensation at the surface or at the edges of the windows
- Burglary potential
- Privacy restriction
- Insects intrusion and other natural elements.

Issues on Thermal Comfort

Bare windows (without curtains or other treatments) have a strong effect on thermal comfort. Even double glazed windows, typically have the lowest U-values and hence the lowest surface temperatures and the strongest impact on median radiant temperature. It has been estimated that as much as 45% of the heat loss from our bodies is through radiation. Objects radiate heat to us at a rate proportional to the fourth power of their absolute temperature. Hence if these objects are cooler than we are we are radiating more energy than we are receiving in return. Therefore the closing of curtains and shutters are tied directly to personal comfort. There is much likelihood the occupants will in fact use them to feel more comfortable and will be warm at a lower thermostat setting. (Wilson and Belshe, 1987)

In winter, in the intermediate neighbourhood of a typical window, the temperature varies smoothly from indoors to outdoors. [...] The decrease is especially steep at locations very close to a glazing sheet (glass pane).' see Figure 15, (Shurcliff, 1980, p.12)

Thermal discomfort in winter near glazed surfaces is also 'due partly to downdraughts, caused by the cold inner surface of the window. In summer, discomfort is primarily from overheating by solar gain and by heating of the person by direct radiation. ' (Baker and Steemers, 2002, p.107)

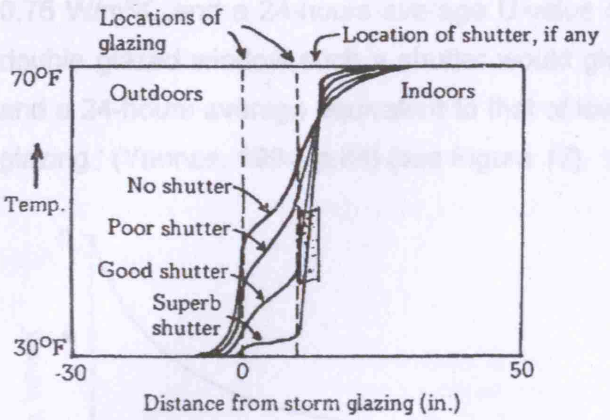

Figure 15: Temperature gradation near storm window (Shurcliff, 1980, p.13)

Active controls & automations

The peaks in heat loss occur when there is no sun to compensate with solar radiation. According to the movement of the sun heat gains and losses fluctuate. 'At UK latitudes 50-60˚ N there is no solar radiation for 60-75% of the time in winter.' (Yannas, 1994, p.84) (Figure 16).Thus, the best performance of windows could be achieved by adjusting the windows properties according to these fluctuations.

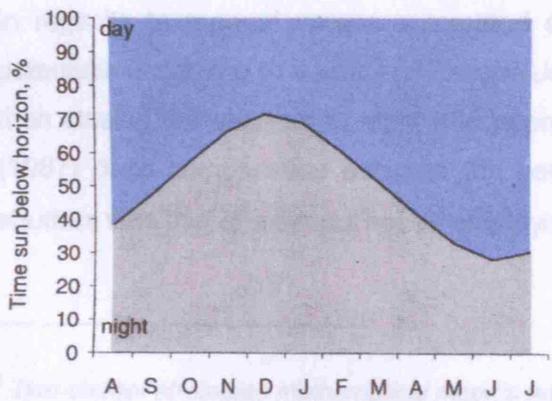

Figure 16 Percentage of time sun is below and above the horizon averaged for the U.K. (Yannas.,1994, p.84)]

Night insulation of glass by substitution or addition of an insulated material, e.g. by a shutter or curtain could be much effective. 'For example, based on typical data for material properties a shutter containing some 35mm of insulation material with a thermal conductivity of 0.035 W/mK can provide a thermal resistance of 1.0 m²K/W, with the air space between shutter and glazing providing a further 0.16 W/m²K. Closed over a single glazed window for twelve hours a day this would give a 'night U-value' of around

0.75 W/m²K, and a 24-hours average U-value equivalent to that of double glazing. On a double glazed window such a shutter would give a night U-value of around 0.65 W/m²K and a 24-hours average equivalent to that of low-emissivity-coated double glazing or triple glazing.' (Yannas, 1994, p.84) (see Figure 17)

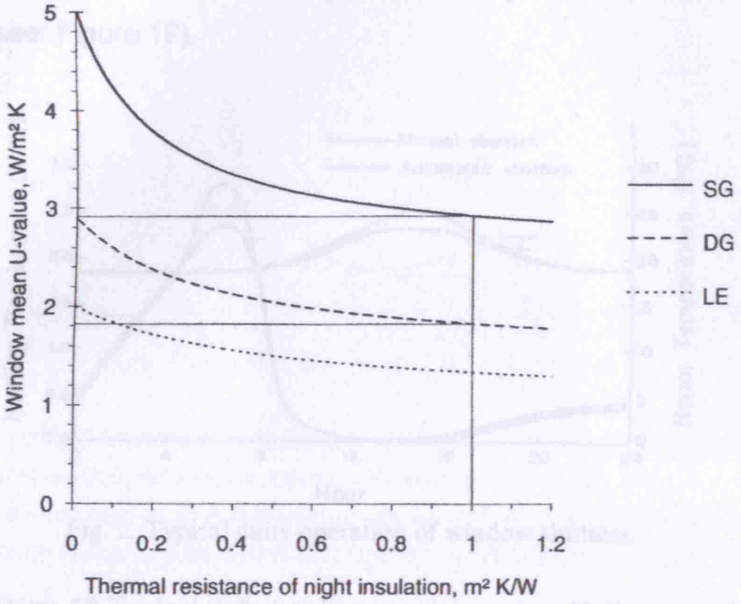

Figure 17 Mean window U-values (24-hour averages) with night insulation; Calculated for windows with wooden frames and normal exposure.(Yannas S.,1994, p.84)

In regards to manual versus automated shutters occlusion the latter has much more potentials according to a study of Zaheer-Uddin (1987). Usually people could do not more than closing the shutters at night and opening them again in the morning. Zaheer-Uddin (1987) drew comparisons between the performances of a house employing automated shutters with that of a similar house employing manual shutters. [5]

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[5] *Two shutter strategies mathematical models were modelled:*

- *a manual strategy in which shutters would open at sun rise and close at sun set*
- *and an automated strategy in which the shutters control strategy depends on weather conditions, opening from a full on/completely off to an intermediate value necessary to maintain the house within allowable temperature limits*

In particular shutters remain:

- *almost closed (a minimum amount of aperture is left for sunlight) at dawn and if there is net heat loss through the windows,*
- *wide open when there is solar radiation and the room is kept within a specified temperature range and without heating on*
- *partially open when there is solar radiation and the room temperature exceeds a certain limit.*

The net results over one full day the automated house consumed 3% less energy for heating than the manual house. (see:
Figure 18). Reductions were dramatic in the hours of overheating (see: Figure 20). The study showed that energy savings employing automations were marginal in houses with low insulation levels and significant for high insulation levels, and thermal massive houses. (see: Figure 19).

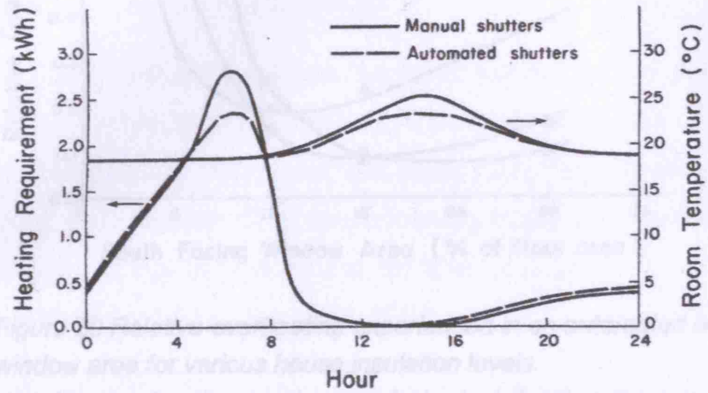

Fig. 2. Typical daily operation of window shutters.

Figure 18 Typical daily heating requirements with the use of window shutters. (Zaheer-Uddin M., 1987, p.70)

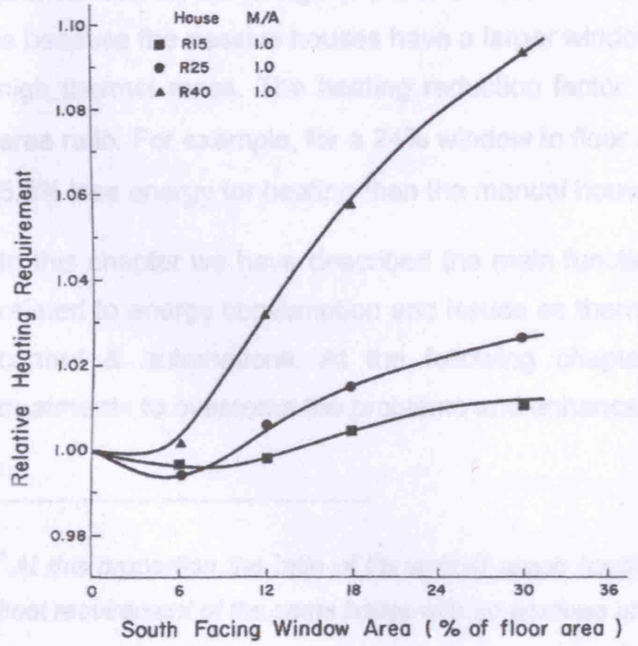

Figure 19 Relative heating requirement of an automated house as a function of south facing window area for various house insulation levels.
(three types of house insulation levels were tested R15, R25 and R40; augmenting from the lowest to the highest insulation capacity. Relative heating requirement factor is defined as the annual heating factor of the manual house to that of that automated house)'(Zaheer-Uddin M., 1987, p.71)

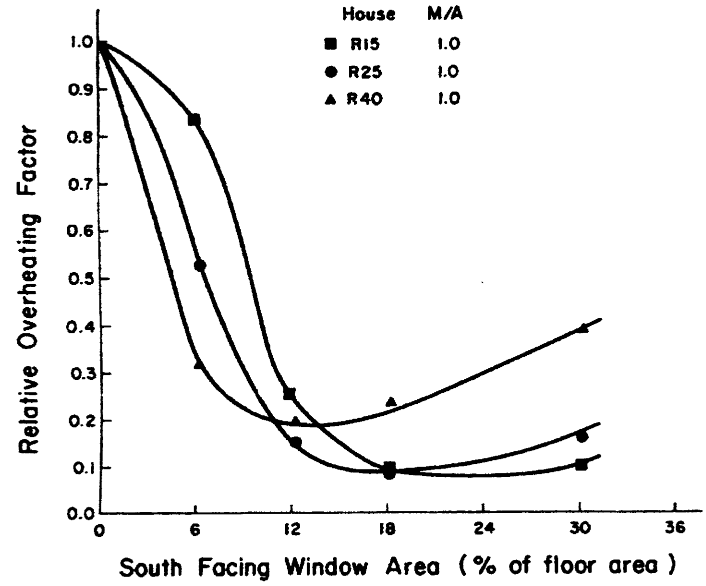

Figure 20 Relative overheating experienced in an automated house as a function of south facing window area for various house insulation levels.
(relative overheating requirement factor is defined as the annual overheating factor of the manual house to that of that automated house)' (Zaheer-Uddin M., 1987, p.71)]

Zaheer-Uddin (1987) supports that 'the influence of automated shutters is more pronounced on the design of passive houses than it is on the energy savings alone.' That is because the passive houses have a larger window area than typical houses, and usually high thermal mass. The heating reduction factor is also relevant to the window to floor area ratio. For example, for a 24% window to floor area[6] the automated house will require 5.8% less energy for heating than the manual house. (Zaheer-Uddin, 1987)[7]

In this chapter we have described the main functions of windows, benefits and problems related to energy consumption and issues as thermal comfort in proximity to windows and control & automations. At the following chapter we will describe technologies and treatments to overcome the problems and enhance the benefits generated by windows.

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[6] *At this proportion the ratio of the annual space heating requirement of the house to the annual heat requirement of the same house with no windows at all reaches its minimum value*

[7] *Furthermore, as thermal mass is considered to be one of most expensive elements in a passive house considerable savings could be made, because the automated house would require about 25% less thermal mass than the manually operated house for the same energy consumption.*

Technologies improving windows performance

Advanced glazing technologies

As mentioned previously the resistance of heat loss by conduction provided by the glass panes is negligible due to its thickness. However heat is transferred through radiation and convection as well, actually the heat loss by radiation exchange of clear glass is the greater heat loss by conduction. [8]

Applying low-e coatings to the inner surface of the pane reduces radiative emission by 96% (i.e. e=0.04) (see Table1). "There are two types of low-e coatings: sputtered (soft) or pyrolytic (hard). In general, soft coats have lower emissivities (0.04 to 0.15) but also lower solar transmission. They are extremely fragile [...] Hard low-e coatings have emissivities of about 0.2, but they are more durable, and some of them have almost no effect on solar transmission" (Hestnes et all, 1997, p.23).

Glazing specification	U value W/m^2K	Light transmittance
Single	5.4	0.87
Double	2.8	0.75
Triple	1.9	0.65
Double low-e	1.8	0.74
Double low-e argon	1.5	0.74
Triple low-e argon	0.8	0.63

Table **1** *: U-values and light transmittance values for various glazing types.*
(N Baker & Steemers, 2002]

Another way to control thermal resistance of glazing is to inhibit convection within air space. This can be optimized by cellularizing air space with transparent insulation

[8]*The application of multiple layers of glass gave opportunities in increasing glazing thermal resistance.* When applying extra layers of glazing we should bear in mind that each layer reduces solar transmission and thus solar heat gains. "In warm countries, double-glazed windows are used, whereas in cold climates designers opt for triple and quadruple glazing systems" (Hestnes et all1997, pp.23,). *Air itself is one of the worst conductors of heat. 'The optimum air space thickness in normal double glazing [...], where the minimum heat loss occurs, is about 10 and 20 mm. (Everett, 1994, pp.3-10) Beyond this limit natural convection currents can easily circulate. Inert gasses can replace air as they have lower conductivity. Argon is the most commonly used because it is cheaper, but krypton and xenon are also used.*

materials that according to Compagno A., (2002 p.80), they can be classified into four geometric structure types: (see Figure 21)

i. structures parallel to the exterior surface
ii. structures perpendicular to the exterior surface (such as louvers, honeycomb and capillaries)
iii. cavity structures (such as bubble structures, e.g. acrylic foam)
iv. quasi-homogeneous structures (such as aerogel, granular aerogel and xerogels)

The materials commonly used for transparent insulation are glass, acrylic glass (PMMA), polycarbonate (PC) and quartz foam.

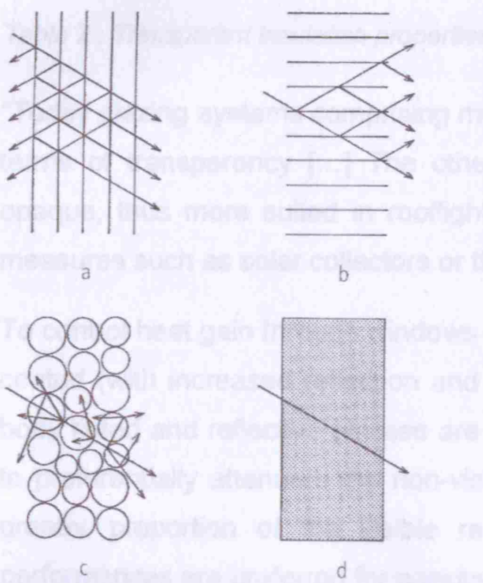

Figure 21 : The 4 geometric structure types of transparent insulation [Source: Compagno, 2002, p.80]

Figure 22 : Insulating glass with integrated capillary structures [Source: Compagno, 2002, p.81]

Among the technologies to control heat loss through glass is the lots promising evacuation of the air space between panes. The main problems of this technology are:

- difficulties to maintain the sealing in a durable way and to avoid thermal bridges at the edges
- the fact that air pressure on the outside, causes the panes to deflect and collapse inwards. (Button and Pye, 1993, p.135)

Development is being carried out in combining vacuum in the cavity filled with aerogel.

The following Table **2** accumulates the properties of some transparent insulation constructions as indicated in the book of Compagno (2002).

TIM Construction	diffuse transmission	U-value (W/m²K)
100 mm honeycomb polycarbonate structure (PC)	0.57	0.80-0.90
100mm cappilary sheet made from acrylic tubes (Oka-lux)	0.69	0.89
20mm filling with aerogel	0.69	0.7
20mm filling with aerogel with vacuum in the cavity	0.69	0.37
16mm granular aerogel	0.41	0.8

Table 2 : Transparent insulation properties (Compagno,2002)

"Today glazing systems comprising multiple panes of glass or plastic films lead the field in terms of transparency [...] The other structures are more or less light-scattering and opaque, thus more suited in rooflights or parapets, as well as in passive solar energy measures such as solar collectors or thermal store walls." (Compagno, 2002, p. 84)

To control heat gain through windows body tinted (with increased absorption), or reflecting coated (with increased reflection and usually also absorption), or even a combination of body tinted and reflective glasses are developed. "Some body tints and coatings are able to preferentially attenuate the non-visible solar radiation, leaving the transmission of the greater proportion of the visible radiation largely unchanged [...] Such preferential performances are preferred for passive solar applications" (Button and Pye, 1993, p.160)

Another way to eliminate heat gains through glass is to incorporate blinds and louvers between the panes. Such fillings can cause a rise in temperature in the intermediate space. There are available louver systems products that "can be adjusted by means of a magnetic control operated from the outside of the insulating glass unit. Depending on the colour, coating and angle, g-values of 0.11 to 0.77 can be achieved." (Compagno, 2002)

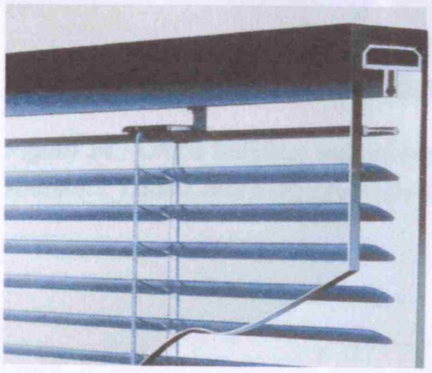

Figure 23 : Glass with integrated adjustable louvers. (Source: Compagno, 2002, p.86).

The double-skin façades

Another way to control glass surfaces is through double-skin facades. The basic advantages of a double skin façade are to protect buildings from the influences of weather, air pollution and external noise. The benefits in overheating control is that double-skin facades allow ventilation that otherwise wouldn't be possible to supply due to pollution, noise or high winds and even to secure night time ventilation. (Hertzsch, 1998) Shading devices could also be supplied at the in-between cavity where the intermediate space could serve convenience at their maintenance and access.

During overheated period: "As reradiation from absorbed solar radiation is emitted into the intermediate cavity, a natural stack effect results, which causes the air to rise, taking with it additional heat." (Compagno, 2002, p. 118)

During underheated period heat losses are reduced due to the function of the cavity as a thermal buffer, the reduced transmission heat losses and the improvement of the thermal comfort because the internal surface area is not exposed to the very cold exterior. (Hertzsch, 1998)

There are several types of double skin facades according to the type of construction and to the type of ventilation, but they are not going to be further analyzed in this study as the functions are complicated.

Figure 24 : Office building, with storey-high cavity and fitted textile blinds
Architect: Leon / Wohlhage (Compagno., 2002, p.125)

Exterior shading devices:

The exterior devices can be divided into three categories – retractable, adjustable and fixed. The retractable can be completely or partially removed from the aperture. The adjustable have the advantage that they can change their light transmittance characteristic as by adjusting the angle of slats.

Horizontal overhang: Among the fixed devices the most simple and common is the horizontal overhang. An alternative to the horizontal overhang is a canopy that can have a mechanism to retract when sunlight is welcomed. It is suitable only for south or close-to-south orientation as its function relies upon the solar path geometry and is effective against high-angle summer sun. However, it obstructs the diffuse light as well. A solution to this problem is the lightshelf that is practically dividing the window vertically: the lower part is protected by the overhang whereas the upper part provides illuminance through reflections at the depth of the space.

Louvers: Their main advantage is that by tilting the slats the light transmittance can be varied. 'When louvers are 45° above horizontal (inside to outside), light transmittance is at a maximum [...] However when used in a defensive mode, louvers are most often set at an angle above horizontal. [...] Louvers that are light colored light transmission is partially by interreflection. This results in the blind becoming a diffuse light source itself as well as a source of ground-reflected light.' (Baker, 2002, p. 114) (see Figure 25)

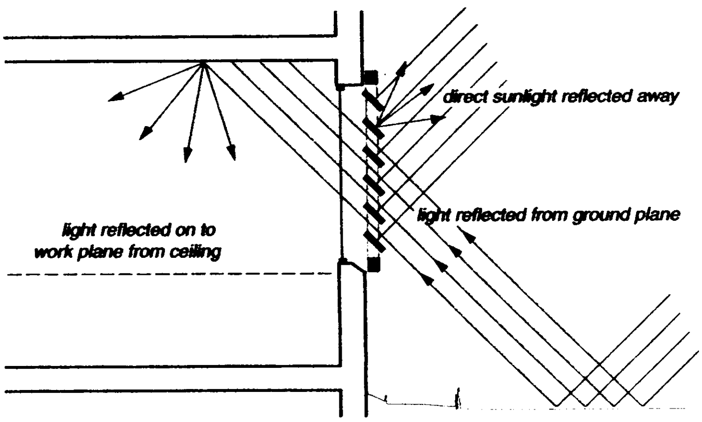

Figure 25 : Louvers allowing ground-reflected light to illuminate the ceiling. (Baker, 2002, p. 113)

Fixed screens and eggcrate baffles: Eggcrate baffles provide good control of solar gain at east and west orientation. Fixed screens, however, are not recommended in temperate climates as the reduction in useful daylight is the same as the reduction in unwanted radiation.

The following window treatments are examined more thoroughly. Those are insulating and dynamic devices curtains and roller blinds, interior and exterior shutters. Most of the following data are accumulated from journal articles. They are mainly focused in interior devices and to the reduction of the winter heat losses for cold northern climates.

Draperies and Curtains

Traditionally, windows were treated to three types of curtains: a sash curtain (to filter light), a draw curtain (to block out light), and an over-drapery (which was purely decorative).

A 1974 study of Dix and Lavan 'Determined that the medium-colored drapery with a white plastic backing reduced conductive heat loss in the winter by 6 to 7 percent, and conductive and radiant (solar) heat gains in the summer by 33 percent.' They also concluded that the material's capacity to **block airflow** was more important than other properties.

A dual study from Horridge et al (1983) and continued from Woodson et al (1983) tested thermal and solar optical properties of interior window treatment (among them curtains, draperies, louvered or fabric shutters ,roller shades, etc.) at variable distances from the glass surface. They claimed that 21 per cent of heat loss can be reduced if draperies are in a tight closure to the centre of the window and around the periphery of the window.[9]

On the first paper they examined the treatments' ability to provide both thermal insulation and to facilitate interior lighting. The summary of the measurements results are shown in Table 26 of Appendix A1. According to the study 'a shutter frame with fabric installed 2.54cm from glass resulted in one of the higher R-values (2.14) with visible light transmittance of 0.41.[10] The study comes to the conclusion that 'the thermal insulation is effective only when the window treatment and glass surface are in **close proximity** (2 cm or less). A normal spacing of 12cm, with a sill, allows too much free space and enhances convective rollover.' (Horridge et al, 1993, p.49).

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[9] *Their experiment design was based on a simulation of a cold box positioned over the exterior surface of a test window, used to simulate cold, night-time conditions on a continuous basis. The wind effects were not simulated.*

[10] *A window treatment with the same fabric shirred between top and bottom rod pockets at the same distance, had an R-value of 2.15 and a visible light transmittance of 0.45.' (Horridge et al, 1993, p.48).*

The second study of Woodson E. et al served to test the solar reflectance, transmittance and absorptance of the same window treatments (Table **27** of Appendix A1). 'Solar **reflectance** is most important in affecting the shading coefficient and the solar heat gain. Hence, a rather high value of reflectance is needed to avoid temperature rises from solar heat gains during summer.' For cold conditions 'treatments having low reflectance and high transmission become the obvious choice.' (Woodson et al, 1983, p.45)

With the elapse of seasons and the various orientations of the windows 'no single treatment can fulfil all the possible requirements placed upon window areas. It is only by combinations of treatments and a concept of **management** that the window becomes fully functional.' (Woodson et al, 1983 p.45)

When Nicol (1986) monitored several drapes and shutters in real case household[11] his results showed that either insulated or foam-backed drapes are apparently no more effective than transparent sheer curtains.[12] Among the window coverings that he tested internal insulated shutters (of 2.5 cm beadboard insulation) inserted in the window frame (from 18.00pm to 08.30 am next morning) were proved to be by far the most effective treatment with approximately 16% energy savings at external temperatures around -10° C, 12% at 0° C and minimal savings when over 10° C, i.e. more substantial savings were observed in colder weather (see Figure 26)

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[11] The researcher tested four drapes composed of a variety of materials over winter period in Canada. The method was based on the monitoring of each window treatment in an unoccupied house by two shielded thermistores mounted on either side of the window covering.

[12] *'This result is likely because these drapes hang so loosely and do not seal against the widows and consequently cold air can easily pass around the base and the edges of the treatment.' (Nicol, 1986, p. 234)*

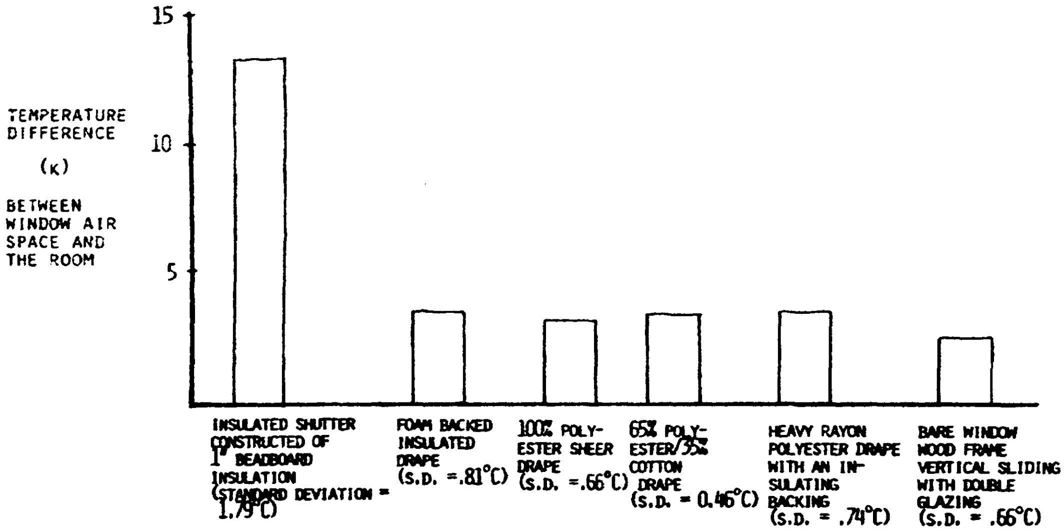

Figure 26 : Temperature difference for various window coverings. (Nicol,1986, p.233)

Internal roller blinds

Roller blinds are composed of a variety of materials from 100% polyester sheer, heavy foam-backed drape or reflective sheets. They can be opaque, translucent or transparent. They may consists of one or more flexible layers that can be rolled up when not needed and usually aim to prevent from solar radiation and glare. (a shutter can also roll up but the difference is that it consists mainly on rigid strips.)

A study about possible energy savings from using interior roller shutters interfering convective and reflective layers was accomplished by Dubbed on 1984 for the Commission of the European Communities. He asserts a 'possible reduction in heat losses up to 50% when two layered rolling shutters and reflective materials are used. A reflective layer on both sides appears to be the most effective to reduce heat losses.' (Dubbed, 1984, p. 322). The weather conditions simulated for testing the treatments of windows can be compared with a cold northern climate. In relation to that; there were no direct solar gains simulated, the outside temperature had a mean value of 5°C and the heating season is 200 days! His study was followed by a cost-benefit analysis that showed that roller blinds and roller screens are in general economically unremunerative (see Table 28, Appendix A1). An exception is the opaque roller blind used on simple glazing.

Internal and external shutters

Shutters consist mainly of one rigid panel or a set of closely connected rigid plates or strips. They can be interior or exterior and may be also placed between the glass panes in storm windows. External shutters are usually found in warm/hot climates, whereas interior in colder ones. They can be opaque, translucent or transparent.

On his previously mentioned study Dubbed (1984) showed comparative tables for several types of shutters with other window treatments. The relative U-value (to a window of 2.5 W/m^2K) is calculated for outside and inside shutters with or without reflective layer with sealed edges or not (see Figure 27) The best performance on reducing heat losses is given by an exterior shutter with comparatively high thermal resistance, sealed edges and reflective layer towards the interior. The study showed the importance of sealed edges and the fact that reflective material in the cavity between the window and the shutter is most effective. There is not significant difference at the performance between exterior and interior shutters if assumed perfectly sealed.

A study in Denmark by Saxhof (1982, cited Byberg et al.,1985) showed that external insulated shutters consisting of 35mm-75mm mineral wool or polystyrene foam would result in annual energy savings of 40-72 kWh/m^2.' when calculated with the degree day method. After the houses with the shutters in real case were inhabited it 'has been proved that that these figures correspond very well to the actual energy savings when the houses are inhabited.'

Byberg et al in (1985) continued this study by testing internal insulated shutters and shutters between two layers of glass. They were constructed of 300mm of Polyisocyanurate foam of a thermal conductivity 0.025 W/mK. Internal insulating shutters resulted in a U-value of 0.68 W/m^2K for 250mm distances from the window whereas for 100mm distance the U-value was 0.67 W/m^2K.[13] According to this the annual energy saving for a typical Danish single family house calculated by means of the degree day method was be about 70 kWh/m^2.When the shutters were arranged between panes 'the measurements showed that when they were in active position, the U-value was 0.91 W/m2K, and the annual energy saving would be about 45 kWh/m^2.

[13] 'The present day value method has been used for finding the maximum cost-effective investments. The analysis indicates that the internal shutter will have to have a lifetime of about 10 years to make the investment cost- effective and the shutter between the panes will have to have a lifetime of about 20 years.' (Byberg et al,1985, p.6)

	Relative U value calculated in % shutter $\Delta R = 1\ m^2K/W$	
Outside		
	not reflect	reflective
not sealed	85	80
sealed edges	25	20

Remarks	Relative U value in %. Shutter without heat resistance.		
Outside			
	not reflect	reflective	reflective
not sealed	90 (82)	90 (85)	82
sealed edges	70	70	42
Inside			
	not reflect	reflective	reflective
sealed edges	70 (76)	55	42 (49)

Figure 27: Calculated and measured relative U values in % to a window of U-value= 2.5 W/m^2K (Dubbled, 1984, p. 319]

2. Designing the integral thermal shutter

Methodologies in the design of shutters and shades

Integral design

2. Designing the integral thermal shutter

Methodologies in the design of shutters and shades

When it comes to designing a façade element such as a shutter or a shading device there are 5 criteria to take under consideration as mentioned by Steve Mudie (during the lecture of "Façade Engineering' organized by Cibse on June 2007):

- The Architectural Intensions
- The Cost of the construction
- The resulting building energy performance, (so as to comply with the Building Regulations, or to achieve a high rating value on its environmental assessment as the BREEAM rating system or EcoHomes of BRE)
- The buildability and durability of the device
- The Procurement of the materials, i.e. the resource capacity.

Figure 28 : Several images of shutters
[Source: Compagno A., 2002, p.125]

None of these criteria should be seen independently. The market gives the primal choice on the architectural intensions.[14] However the architectural design needs justification in order to support its existence. Design inspiration comes together with the knowledge of the context where the building is to be placed and the building's function and expectations. When it comes to facades, any exterior shutter or shading device is also morphologically much evident. (see Figure 29)

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[14] Olgyay & Olgyay (1957) also believe that 'Architectural expressions should grow from the ground of objective analyses-and the realm of feelings, the emotional content, should draw its synthesis beyond the technical level. Then can architecture –by fulfilling its dual role of satisfying emotional and physical needs-develop its true expression.'

There are guides that give criteria to control heat loss and gains as Olgyay & Olgyay's book 'Solar Control and Shading' (1957) and as Shurcliff's book 'Thermal Shutters and Shades" (1980) when designing window devices.

Figure 29 : Exterior shading devices evident on the façade.

The method of Olgyay & Olgyay is analyzed into 4 steps:

Step 1: Determines the times when shading is needed

Step 2: Determines the position of the sun, at these times

Step 3: Determines the type and position of a shading device which will interfere between the sun and the point of observation.

Step 4: Finally proposes the shape of the shading device according to the shading mask.

Every shading device either horizontal, vertical or eggcrate can be plotted on a protractor (see Figure 30) and by overlaying the shading mask in the proper orientation on the sun-path diagram, one can read off immediately the times when the sun's rays will be intercepted. His book ends up in a catalogue with several shading masks categories (see Figure 31).

Figure 30: The protractor
(Olgyay & Olgyay, 1957, p. 88)

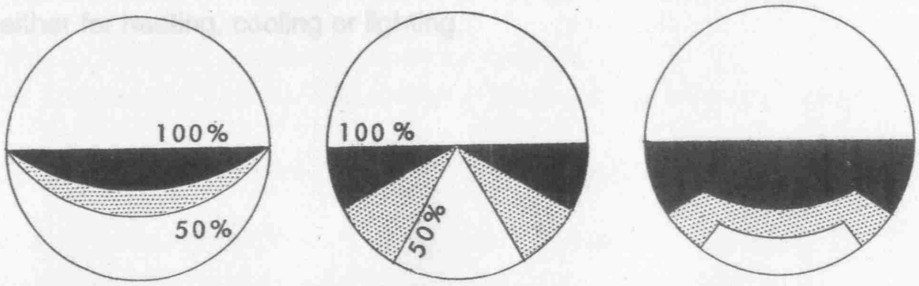

Figure 31: Shading masks of a. a horizontal overhang, b. vertical fins, c. eggcrate shade
(Olgyay & Olgyay, 1957, pp. 89-92)

Shurcliff on the other hand in his book 'Thermal Shutters and Shades" (1980) gives over 100 schemes for reducing heat-loss through windows. He enumerates a bulk of choices between:

- interior or exterior devices,
- devices that hang, slide, fold, or roll up
- devices that consist of thick, strongly built assemblies, or simple lightweight plates, or thin flexible sheets
- devices that rely mainly on trapped air, or on thick foam, or on reflective aluminium surfaces
- devices that employ formal seals, informal not-so-tight seals, or no seals at all
- devices that remain in view and ready for use throughout the year, selectively part of the day or part of the season

- devices that are integral part of the walls and are installed while the house is being built, or are designed for retrofit
- devices that work in combination or act supplementary with others, such as curtains
- devices designed mainly for beauty, or mainly for utility' (Shurcliff, 1980).[15]

The book of Shurcliff takes no account of the shading benefits of a device neither does the book of Olgyay & Olgyay (1957) take into account the reduction of heat losses by occluding a device. For the latter 'the effectiveness of a shading device depends on the proportionate success with which it covers a given surface during the overheated period without interception of the sun's energy during underheated times.'

I would say that the success of a fenestration system is to include both functions: heat loss and shading control, if not more (noise control, privacy provision, safety from burglary, screening from insects, glare and wind protection, to name a few). The interest of this study concentrates on energy savings hence it deals with devices that can save energy either for heating, cooling or lighting.

Integral design

Moreover, the value of a shutter rises when it serves more than one purposes. Apart from energy savings a shutter can offer more benefits that could rise the comfort, safety and pleasure and eventually the its value.

When designing a window treatment device it is worth designating the functions that the shutter is expected to offer. The following Table **3** shows the potential functions of alternative fenestration systems.

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[15] *Although he gives a bulk of alternatives at the end he provokes homeowners –rather than architects - to consider using roll-up shades that include aluminized sheet, or use simple-not permanently attached insulating plates. He acknowledges the practicality of devices that can be left in place continually such as added sheets of glass, transparent or translucent plastic*

Fenestration system	Possible Functions Offered					
	During the day				During the night	
	Privacy-looking in-	diffusion	sun rad-protection	dalight control	Privacy-looking in	energy
Lace or net curtains	•	•				•
Curtains and draperies (open during the day)			•	•	•	•
Normal roller blind	•		•	•	•	•
Vertical or horizontal blinds	•	•	•	•	•	•
Roller shutters						
Not transparent - two side reflective			•	•	•	•
Reflective on one side			•	•	•	•
Transparent-reflective on two sides	•	•	•			•
the above functions correspond to the usual opening regime of each device. The table is taken by the EUR-9225 and was interpreted and increased by the writer						

Table **3** *: Functions of several fenestration systems*
The table is taken by EUR-9225 (Dubbled, 1984) and was interpreted and increased by the author.

Optical and thermal properties of the shutter

Heat is transferred through conduction, convection and radiation. A shutter's thermal conductivity designates this ability so we are usually aiming for a low such value. This insulation capacity is also a function of the thickness of the device.

Since heat is also transferred through radiation the materials' capacity to reflect, absorb and emit or even transmit radiation is a point we should consider when choosing a window treatment device. Those characteristics of the materials may vary depending on the wavelength of radiation. They are attributes of the surface of the material. This gives as the potential to apply just a thin layer on the main material of the shutter.

Another issue to consider when choosing a device material is its transmission capacity. "Designers of thermal shutters and shades usually gravitate to materials that are opaque because (1) most objects with high R-value rugged and cheap are opaque, and (2) such materials insure night-time privacy." (Shurcliff, p.38) Translucent and transparent devices have a great merit; during winter they can be left in place covering the windows night and day, require no attention but also have a great disadvantage; most of the visible light that they let through will eventually transform into heat causing overheating during summer if closed during the day for solar protection.

The tightness of seals and the proximity to the panes

When designing a window shutter we should bear in mind that if seal is tight the convective heat-losses of the pane will be small. A close proximity to the pane confines convective roll over. The shutter will also act as a buffer and will reduce the wind pressure that causes air leakage. The tightness of the seal is important in terms of condensation produced to the glass pane on a cold night especially for interior shutters.

The placement inside-outside or between panes

The placement of shutter between external, internal, and in between panes, is a choice dependent on the climate and the orientation.

Outdoor location: The main distinction when compared with the other placements is that the shutter can be made to do double duty. Besides insulating the window on winter nights, it can intercept solar radiation before entering the building when used during summer day. This is the reason why external shutters are more popular in hot, warm climates. When placed outside it may also tilt so as to act like an awning or overhanging eaves. A significant disadvantage of this location is that the exterior shutters are susceptible to external conditions such as high winds, rain etc. and must be of a more robust construction.
Indoor location: Provision should be made for the placement of the shutters during the daytime, as they may occupy useful interior space. The construction doesn't have to withstand outdoor conditions and be very good sealed. These devices are more suitable for cold climates with lots of wind and rain.
In-Between panes location: The device occupies no space and is perfectly protected by outdoor conditions. However the space between the panes may be very small and the shutter has to be thin and this produces restrictions in its design.

When deciding upon shutter's location we should have in mind how condensation appears in its case. Based on Quirouette's, study (1980):

- 'With an inside insulated window shutter it is probable that condensation and perhaps icing will accumulate between the glass and the shutter during prolonged cold spells.' 'To control this it is necessary that the shutter be air tight and that the shutter construction have a high resistance to the flow of moisture from diffusion.'
- 'When the shutter is inserted between two glass panes the inside side of the glass will warm up slightly, thereby reducing any window condensation.'

- In the case of the exterior shutter the potential of condensation is reduced if not eliminated. The air tightness thus is not critical and the diffusion characteristic is immaterial.

Economic criteria

In order to employ high energy-performance window devices, which is the main object of this study, sophisticated materials, constructions and installations may be required which might be costly.

There is a bulk of parameters to take into consideration as resultant energy savings depend on many factors. By considering what is already presented in this study savings are most probable to occur:

- When the climatic conditions are extreme; either cold and long winters or hot summers with high solar radiation
- When the orientation of the building is awkward
- When the windows' U-value is small e.g. single panes. [16]
- When there is leakage of outside air in or of inside air out i.e. the windows are not well sealed and/or there are high winds.
- When the demands in conditioning the interior space are big.
- When the windows to floor fraction is big as in passive houses.

In each case when a fenestration device is to be applied a cost – benefit analysis should be presented in order to support the choice of the device in question.

At this point we completed the descriptive part of the study that showed a historical flashback, examined relevant studies up to now and ended with conclusions in shutters design. This part formed the base for the following part that is the experimental one and consists on a simulating study and a real case experiment study.

---

[16] Shutters 'applied to single-glazed windows in cold regions, such devices may pay for themselves in 1 to 4 years and may provide profit of $1/ft² each year thereafter. Applied to double-glazed windows the payback period is about twice as great, i.e., still acceptably short. In warm regions, inexpensive low-R devices applied to single-glazed windows may pay for themselves in 2 to 6 years, but if the widows are double-glazed the devices must be extremely-low-cost type if they are to be cost-effective.' (Shurcliff, 1980):

3. Simulation

The methodology

Simulation Part 1 –Planar Thermal Shutters

Simulation Part 2 – Louvered Thermal Shutters

Analysing and Examining Parameters

3. Simulation

The methodology

There are several methods to assess the thermal effectiveness of fenestration systems: that would either be mathematical models, experiments in climate chambers[17] or real cases monitoring. In the best case the computer simulation should support its conclusions with real case observations. However, the latter method is time consuming because the results are more trustingly if tested for longer periods. This is because either there is the need of a preconditioning period so that the real case environment comes to equilibrium, or there are fewer possibilities for errors due to exceptions usually in occupants' behaviour and weather.

The methods chosen for this study is the use of Energy Plus software and an experiment in a real building -described in chapter 4. The limited time of this study restrained the experiment in short periods of time and only during hot summer weather conditions.

"Energy Plus is a building energy simulation program for modelling building heating, cooling, lighting, ventilating, water and other energy flows."[18] It is originally based on the most popular features and capabilities of BLAST and DOE-2. EnergyPlus was chosen because it has numerous capabilities among: simultaneous calculation of radiation, convection, and conduction processes for each time step and loads, daylighting, illumination and controls, advanced fenestration calculations (controllable window blind model coupled to daylight and solar gains, bi-directional shading devices),etc. (U.S. Department of Energy).

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[17] The climate chamber is usually the case of two adjoining boxes separated by an exchangeable test wall (a test frame) with a mounted window; the cold box with a refrigeration system to simulate outdoor weather conditions and the hot box with a pre-fixed "indoor" temperature. Those two methods have the drawback that the fenestrations and the methods of control tested have a certain amount of deviation from real life conditions and occupants behaviour. (Nicol, 1986)

[18] Energy Plus – Version 2.0.0. is available from: http://www.eere.energy.gov/buildings/energyplus/, developed jointly by Lawrence Berkeley National Laboratory, the University of Illinois, the U.S. Army Construction Engineering Research Laboratory, GARD Analytics, Inc., Oklahoma State University and others, with support from the U.S. Department of Energy, Office of Building Technology, State and Community Programs. (The Simulation Research Group at Lawrence Berkeley National Laboratory (LBNL) in Berkeley, California. Available from: <http://gundog.lbl.gov> [Assessed on 05/07/])

The Context and the Assumptions

The model of the simulation is assumed to be a living-room of a dwelling in Greece. In particular the context of the model is described by the following characteristics:

Location: Suburbs of Athens, Greece. Latittude 37.9, Longtitude 23.7

Weather Characteristics: The weather is typical Mediterranean with mild winters, and rather hot summers with high solar radiation. The diurnal variation is around 10˚C during summer and less than 10˚C during winter. The hottest month of the year the average temperature is 27.9˚C whereas the coldest month 9.4˚C (Axarli and Papadopoulos, 1995, p. 238,). The following chart (Figure 32) shows monthly diurnal averages.

Figure 32 : Monthly diurnal averages for the Greek climate.
[Source: The ecotect software]

There are two reasons that the specific location was chosen:

- First for correspondence with the subsequent real case monitoring that took place in Greece. Thus, both studies will work supplementary for each other and affirmation or conflicts between results can be examined.
- A second reason for choosing the Mediterranean climate is because we want to evaluate the performance of the shutters in the case of summer hot weather conditions, as well as cold winter ones and the Mediterranean climate can provide both.

Dimensions of the model: The dimensions of the room are 5.00x5.00m and the window 2.00x1.50m, as shown at Figure 33. The window to floor ratio is: 0.12. A section of the room is shown at Figure 80 of the Appendix A2

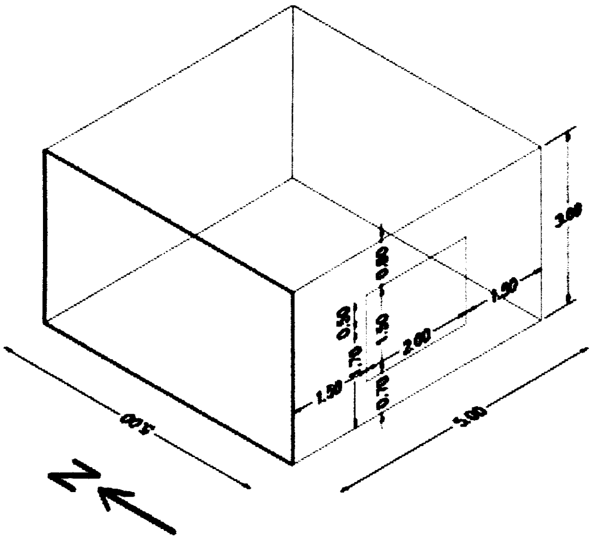
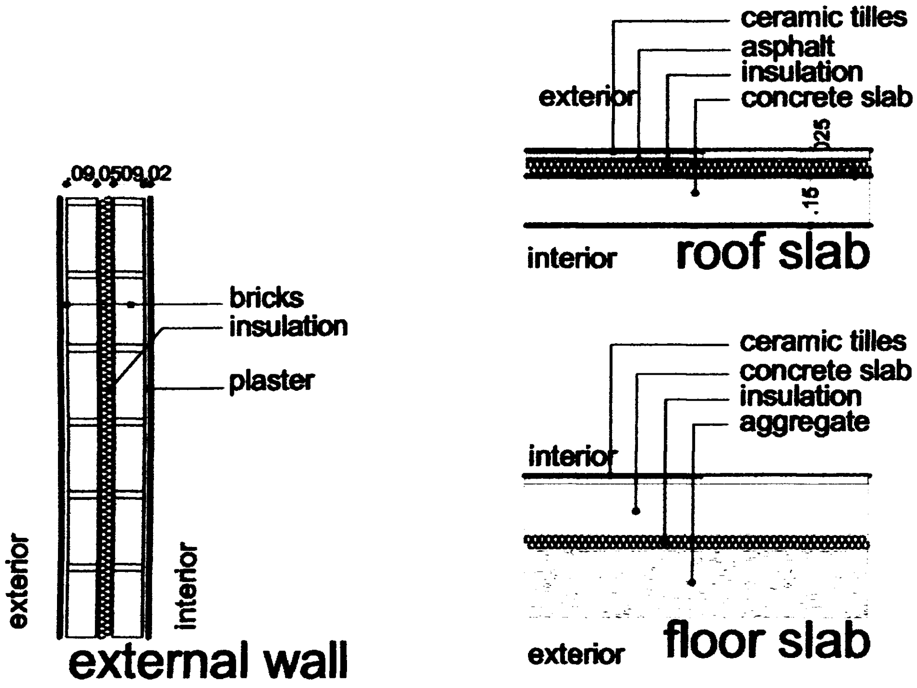


Figure 33 : A 3d image of the simulation model

Orientation: The window of the room faces south direction

The material and constructions: The construction is a typical construction of an existing Greek house simplified for the program and is shown at the following Figure 34. The properties of the materials used in energy plus is shown at Table **29**-Table **35** (Appendix A2). The window pane is made of single glass and its properties are shown at Table **36** Appendix A2).



constructions detail scale 1:20

Figure 34 : Construction details used of the model

The mechanical heating and cooling regime: The simulation model is assumed to have mechanical heating and cooling. This way we can estimate the heating and cooling loads in terms of kWh. However, the study refers to free-running buildings as well. The set points of the thermostats are adjusted at tolerance values according to Nicol and Humphreys' adaptive approach.[19]

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[19] *According to Nicol and Humphreys' adaptive approach study the thermal comfort correlates with the average condition that people are used to experience at the given time of the year. In this case the occupants are used to a mean temperature during the overheated period (May to September) of Tm=25.8°C (for Greek climate). For free-running buildings which gives :*
An upper comfort temperature: Tc = 0,33Tm + 20.8= 0.33x25.8+20.8=29.31
During the period from November to March when the building is more likely to be heated the mean exterior temperature is Tm=11.56°C. For free-running buildings the occupants are used ata lower comfort temperature: Tc = 0,33Tm + 16.8= 0.33x11.56+16.8=20.61

	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June
Mean Monthly Air Temp.- °C	27.9	27.8	23.9	18.7	15	11.4	9.4	10.3	11.7	15.8	20.6	25.2
Relative Humidity-%	46	47	54	66	72	75	73	71	67	62	58	53

Athens' Weather mean monthly values, data taken from Axarli (1995, p.83)

So, the set point for heating is 21°C and for cooling is 29°C. The setback values are 17°C and 21°C respectively from 00.00 – 7.00 am. The heating period in Greek usually lasts from October to April, while the cooling period from May to September. The following Table 4 gathers the adjustments of the set points for mechanical heating and cooling.

	Heating Period 1st October- 30th of April		Cooling Period 1st May - 30 September	
	Day time	Night time	Day time	Night time
Thermostat Set Point	7.00am-00.00	00.00- 7.00am	7.00am-00.00	00.00- 7.00am
	21°C	17°C	29°C	31°C

Table 4: Set points and set back values of the heating and cooling system.

The internal gains and occupancy period: The electric equipment apart from lighting is assumed to be 8 W/m², (total 200 W). The occupancy period of the room is every day from 7.00am-00.00.

Infiltration Rate: An empirical value for air infiltration rate for apartment rooms in 1-5 storey buildings on normally-partially-exposed sites in winter – dwellings would be 0.7 ACH (Cibse Guide A, 2006, table 4.21, p.4-16).[20]

That would give: 0.70x (5x5x3) /3600= 0.0145 m³/s

The lighting: The illuminance requirement of the sitting room is assumed to be 150 lux as indicated by the CIBSE (2002) and can serve casual reading. The type of lamps is assumed to be fluorescent with efficacy 60 lm/W. The total power required for lighting are calculated with the lumen method [21] and is 154W.

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[20] *This value is in accordance with the value indicated from Building Regulations Part L of 2002. i.e. 10.0 m³/m²h at 50 Pa. The Building Regulations of 2005 indicate a value of 7.0 m³/m²h at 50 Pa but since the Greek regulations are not as stringent it was thought sensible to use the value of 10.0*

[21] *According to the average lumen method the total flux requirements is found by the formulae:*

$$\text{Total Flux} = \frac{\text{Required illuminance x Area}}{\text{UF x MF}} = \frac{150 \times 25}{0.45 \times 0.9} = 9259\ lm$$

The UF (Utilization Factor) for a near spherical diffuser, open bellow and reflectance of ceiling and walls 0.7and 0.6 respectively is specified 0.45.

The MF (maintenance factor)= LLMF x LSF x LMF x RSMF. The LLMF (Light Loss Maintenance Factor) for indirect light is specified 0.9 and all other parameters (LSF, LMF, RSMF) are assumed1.

If the lamps' efficacy is assumed to be 60lm/W then the total Watts required would be:

9259/60= 154W

Photocells placement: The lighting requirement is synchronized with the occupancy period of the room (7.00am - 00.00 daily). It is assumed that dimming controls maintain the illuminance level at 150 lux as daylight provides part if not all of the illuminance required. Interior daylight illuminance is calculated at two central reference points as shown on the following

Figure 35.

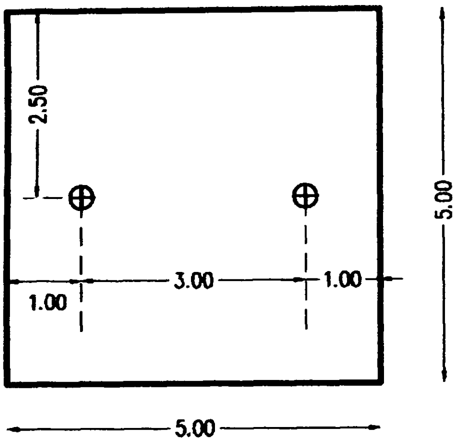

Figure 35 : Placement of the photocells

Description of the series of simulations

At this part of the study we will be running several simulations of various fenestration systems that will by varying their assembly, material's thermal and visual characteristics and control regime. Initial simulation will regard a conventional planar shutter with the simplest opening regime and according to the results the subsequent simulations will involve more complex systems in order to improve shutter's performance.

Factors such as heating, cooling and artificial lighting load will be of our interest. Comparisons of the simulations results will be done each time to assess the each shutter systems with previous ones and at the end a comparison of all will take place.

The simulations are divided in two parts: Part 1 concerns planar thermal shutters and Part 2 louvered thermal shutters.

Part 1 has 6 Control Types. The simulation starts with a planar wooden shutter for which all 6 Control Types will be tested. In the case that a Control Type needs a setpoint value several values will be tested again. Simulations continue with an insulating shutter for which the 6 control types are tested again. The same pattern continues until translucent and aluminium coated shutters are tested too.

Part 2 tests thermal shutters with louvers for 5 Control Types. The simulation starts with wooden louvers and continues with insulating and aluminium coated louvers. For each material all control types are tested. There is a big volume of combinations of setpoints and slat angles for each case and for this reason there was a constraint of the bulk of simulations by using the experience of previous results.

The following two Tables (Table 5 and

Table 6) are an overview of the sequence of simulations. Later, they will serve as a reference point.

PART ONE - PLANAR THERMAL SHUTTERS

Control Type of Planar Shutters	Description
Control Type_A	Always on
Control Type_B	On at winter nights / off during days
Control Type_C	Off at nights /on during days if cooling is on and solar radiation on window exceeds a setpoint value.
Control Type_D	On at nights if outside temperature is lower than a setpoint value / off during days
Control Type_E	On at night if outside temperature is lower than a setpoint value /on days if cooling is on
Control Type_F	On at winter nights /on during days if cooling is on and solar radiation on window exceeds a setpoint value.

Material and Control Type	Setpoint tested
Wooden Thermal Shutter_ Control Type A	-
Wooden Thermal Shutter_ Control Type B	-
Wooden Thermal Shutter_ Control Type C	400, 350, 300, 250, 200, 100W/m²
Wooden Thermal Shutter_ Control Type D	14º, 15º, 16º, 17º, 18º, 19º
Wooden Thermal Shutter_ Control Type E	17º
Wooden Thermal Shutter_ Control Type F	300W/m²

Material and Control Type	Setpoint	Thickness
Insulating Thermal Shutter_ Control Type A	-	50mm
Insulating Thermal Shutter_ Control Type B	-	50mm
Insulating Thermal Shutter_ Control Type PC	300W/m²	50mm
Insulating Thermal Shutter_ Control Type D	17º	50mm
Insulating Thermal Shutter_ Control Type E	17º	50mm
Insulating Thermal Shutter_ Control Type F	300W/m²	50mm

Material and Control Type	Setpoint	Thickness
Insulating Thermal Shutter_ Thickness 100mm Control Type F	300W/m²	100mm

Material and Control Type	Setpoint	Transmission Value
Translucent & Insulating Thermal Shutter_ Control Type A	-	0.40
Translucent & Insulating Thermal Shutter_ Control Type B	-	0.40
Translucent & Insulating Thermal Shutter_ Control Type C	300W/m²	0.40
Translucent & Insulating Thermal Shutter_ Control Type D	17º	0.40

Translucent & Insulating Thermal Shutter_ Control type E	17º	0.40
Translucent & Insulating Thermal Shutter_ Control type F	300W/m²	0.40
Material and Control Type	**Setpoint**	**Transmission Value**
Translucent & Insulating Thermal Shutter_ Control type E	17º	0.30
Translucent & Insulating Thermal Shutter_ Control type E	17º	0.20
Translucent & Insulating Thermal Shutter_ Control type E	17º	0.10
Material and Control Type	**Setpoint**	
Unpolished Alum. & Insul. Thermal Shutter_ Control Type A	-	
Unpolished Alum. & Insul. Thermal Shutter_ Control Type B	-	
Unpolished Alum. & Insul. Thermal Shutter_ Control Type C	300W/m²	
Unpolished Alum. & Insul. Thermal Shutter_ Control Type D	17º	
Unpolished Alum. & Insul. Thermal Shutter_ Control Type E	17º	
Unpolished Alum. & Insul. Thermal Shutter_ Control Type F	300W/m²	
Material and Control Type	**Setpoint**	
Polished Alum. & Insul. Thermal Shutter_ Control Type A	-	
Polished Alum. & Insul. Thermal Shutter_ Control Type B	-	
Polished Alum. & Insul. Thermal Shutter_ Control Type C	300W/m²	
Polished Alum. & Insul. Thermal Shutter_ Control Type D	17º	
Polished Alum. & Insul. Thermal Shutter_ Control Type E	17º	
Polished Alum. & Insul. Thermal Shutter_ Control Type F	300W/m²	

Table 5 : Overview of the series of simulations for planar shutters

PART TWO – LOUVERED THERMAL SHUTTERS

Control Type of Louvers	Description
Control Type_0	Fixed slat angles
Control Type_A	Scheduled to retract winter days and summer nights. Else slat angle is set.
Control Type_B	Scheduled to retract winter days and summer nights. If it is winter night slats close. Else slat angle is set.
Control Type_C	Scheduled to retracted at winter days and summer nights. If it is winter night and if (cooling is on and solar radiation on window exceeds setpoint value) slats close. Else slat angle 90°.
Control Type_D	Scheduled to retracted at winter days and summer nights. If it is winter night and if cooling power exceeds setpoint value slats close. Else slat angle is 90°.
Material and Control Type	**Setpoint**
Wooden Louvers_Control Type 0	0°, 15°, 30°, 45°, 60°, 75°, 90°, 105°, 120°, 135°
Wooden Louvers_Control Type A	0°, 15°, 30°, 45°, 60°, 75°, 90°, 105°, 120°, 135°
Wooden Louvers_Control Type B	60°, 75°, 90°, 105°, 120°,
Wooden Louvers_Control Type C	300 W/m^2, 400 W/m^2, 450 W/m^2
Wooden Louvers_Control Type_D	400 W, 500 W, 600 W
Material and Control Type	**Setpoint**
Insulating Louvers_Control Type 0	120°
Insulating Louvers_Control Type A	90°
Insulating Louvers_Control Type B	105°
Insulating Louvers_Control Type C	450 W/m^2
Insulating Louvers_Control Type_D	600 W
Material and Control Type	**Setpoint**
Polished Aluminium Coated & Insul. Louvers_Control Type 0	0°, 15°, 30°, 45°, 60°, 75°, 90°, 105°, 120°, 135°
Polished Aluminium Coated & Insul. Louvers_Control Type_A	0°, 15°, 30°, 45°, 60°, 75°, 90°, 105°, 120°, 135°
Polished Aluminium Coated & Insul. Louvers_Control Type_B	30°, 45°, 60°, 75°, 90°
Polished Aluminium Coated & Insul. Louvers_Control Type_C	300 W/m^2, 400 W/m^2, 450 W/m^2
Polished Aluminium Coated & Insul. Louvers_D	400 W, 500 W, 600 W

*Table **6** : Overview of the series of simulations for louvered shutters*

Simulation Part 1 –Planar Thermal Shutters

Simulation process of planar shutters

Intro: The initial model will be a very simple planar wooden one. The material characteristics are shown Table **37** (Appendix A2). The air permeability of all shutters examined is assumed to be zero. First simulation to run is that of window without shutters as a comparative base case. Then we are going to perform several simulations for various control strategies (Control Type_A, B, C, D, E, F) as described at the following Table 7. The results of the lighting, heating, cooling and total load are shown at the Table ***8*** whereas Figure 36 and Figure 37 illustrate the annual loads for each control type.

Name	**Description**
Control Types of Planar Shutters	
Control Type A	Always on
Control Type B	On at winter nights / off during days
Control Type_C	Off at nights /on during days if cooling is on and solar radiation on window exceeds a setpoint value.
Control Type_D	On at nights if outside temperature is lower than a setpoint value / off during days
Control Type_E	On at night if outside temperature is lower than a setpoint value /on days if cooling is on
Control Type_F	On at winter nights /on during days if cooling is on and solar radiation on window exceeds a setpoint value.
	note: cooling is on if internal temperature > 29°.

Table 7 : Control types of planar shutters

Materials and Control types	Setpoint	Light. Load - kWh	Heat. Load - kWh	Cool. Load - kWh	Total Load - kWh
Wooden Thermal Shutter					
No shutter (base case)		331.09	549.94	618.59	1499.62
Control Type_A		955.57	691.66	439.73	2086.95
Control Type_B		331.09	456.86	618.59	1406.54
Control Type_C	300W/m²	422.76	549.94	410.87	1383.57
Control Type_D	17º	331.09	432.23	619.39	1382.71
Control Type_E	17º	532.97	432.23	414.43	1379.63
Control Type_F	300W/m²	422.80	456.94	411.45	1291.19
best choice: Control Type_F	300W/m²	422.80	456.94	411.45	1291.19
% variation from base case		-27.70	16.91	33.49	13.90

*Table **8** : Annual loads of planar wooden shutters*

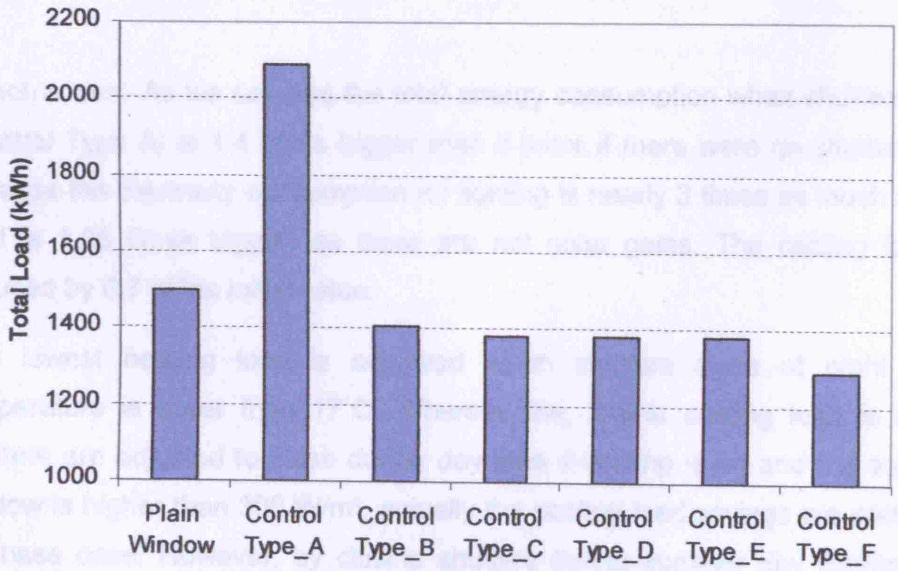

Figure 36 : Total annual loads for several control types of planar wooden shutters

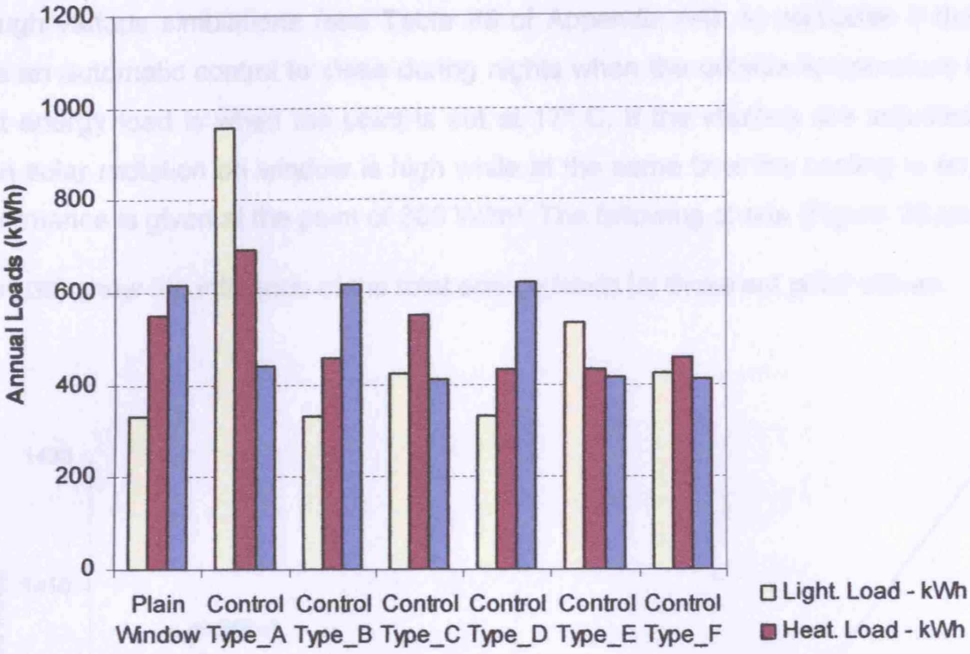

Figure 37 : Annual lighting, heating and cooling loads for several control types of planar wooden shutters

Conclusions: As we can see the total energy consumption when shutters are always on (Control Type A) is 1.4 times bigger than if there if there were no shutters at all. That is because the electricity consumption for lighting is nearly 3 times as much and the heating load is 1.25 times bigger, as there are not solar gains. The cooling load however is reduced by 0.7 of the initial value.

The lowest heating load is achieved when shutters close at night if the outside temperature is lower than 17˚C. Whereas the, lowest cooling load is achieved when shutters are adjusted to close during day time if cooling is on and the solar radiation on window is higher than 300 W/m², actually the cooling load savings are pretty high; 33% of the base case. However, by closing shutters during summer day lighting load rises by 27.7%. Even so, the lowest total energy load achieved is when shutters close during winter nights and during days when cooling is on and solar radiation on windows is more than 300 W/m² (Control type F). (Note that cooling is on if interior temp.>29˚C).

The way optimal quantities for the set points of control strategies C and D were defined through various simulations (see Table ***46*** of Appendix A4). In particular if the shutters have an automatic control to close during nights when the outside temperature is low the least energy load is when the point is set at 17º C. If the shutters are adjusted to close when solar radiation on window is high while at the same time the cooling is on, the best performance is given at the point of 300 W/m². The following charts (Figure 38 and *Figure 39*) show the influence of the total energy loads by those set point values.

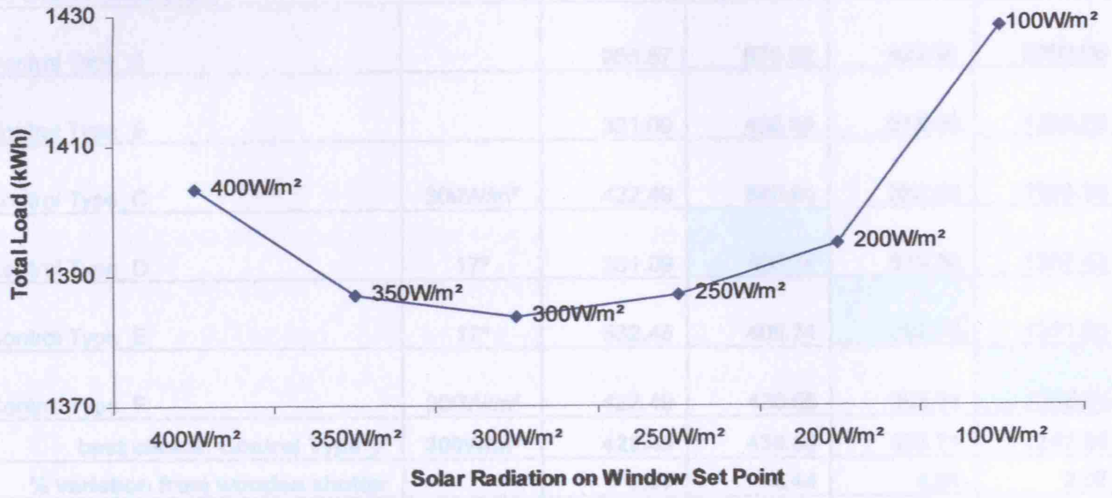

Figure 38: Total energy load as a function of the setpoint of control type C

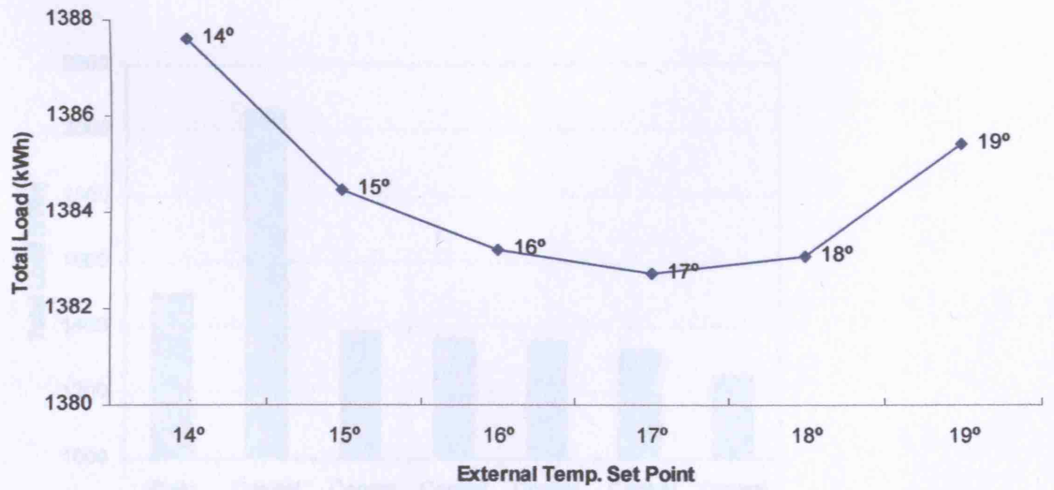

Figure 39: Total energy load as a function of the setpoint of control type D

Intro: Following, we will test shutters with insulative capacity and then shutters with light transmission as well (as with translucent insulation). The insulative material used has a thermal conductivity of 0.035 W/mK while all other thermal attributes are kept unaltered (Table 38, Appendix A2). The results of the simulation are shown at Table **9** and at the chart of Figure 40.

Materials and Control types	Setpoint	Light. Load - kWh	Heat. Load - kWh	Cool. Load - kWh	Total Load - kWh
Insulating Thermal Shutter					
No shutter (base case)		331.09	549.94	618.59	1499.62
Control Type_A		955.57	675.52	427.97	2059.06
Control Type_B		331.09	436.58	618.59	1386.26
Control Type_C	300W/m²	422.49	549.94	392.93	1365.36
Control Type_D	17º	331.09	406.74	619.59	1357.42
Control Type_E	17º	532.48	406.74	392.73	1331.95
Control Type_F	300W/m²	422.49	436.65	393.71	1252.84
best choice: Control Type_F	**300W/m²**	**422.49**	**436.65**	**393.71**	**1252.84**
% variation from wooden shutter		**0.07**	**4.44**	**4.31**	**2.97**
% variation from base case		**-27.61**	**20.60**	**36.35**	**16.46**

*Table **9** : Annual loads of insulating planar thermal shutters*

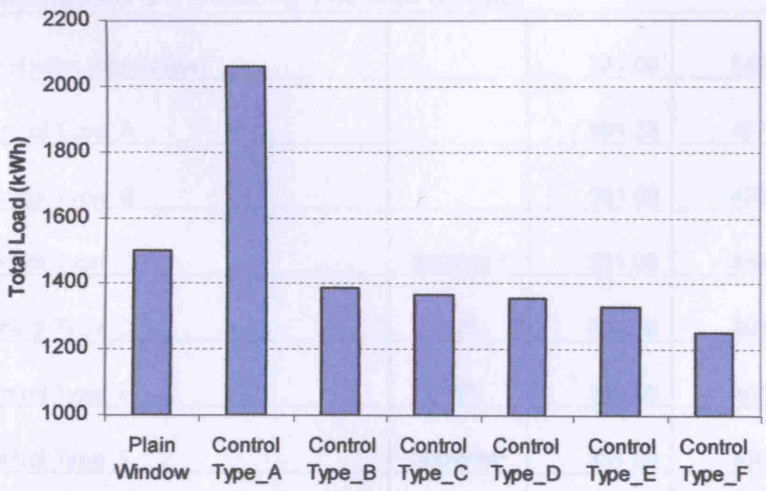

Figure 40 : Total annual loads for several control strategies of planar insulating shutters

Conclusions: The savings when using insulating shutters are small. We succeeded in reducing total energy load by 3% compared with the use of wooden shutters. By doubling the thickness of the insulation i.e. 100mm the total load is further reduced by 1% as shown at Table ***10*** . We should also bare in mind that thickness posses restrains at the design and construction of shutters.

Materials and Control types	**Setpoint**	**Light. Load - kWh**	**Heat. Load - kWh**	**Cool. Load - kWh**	**Total Load - kWh**
Control Type_F	300W/m²	422.41	429.08	387.74	1239.23
% variation from previous		**0.02**	**1.73**	**1.52**	**1.09**
% variation from wooden		**0.09**	**6.10**	**5.76**	**4.02**
% variation from base case		**-27.58**	**21.98**	**37.32**	**17.36**

*Table **10** : Annual loads of insulating planar thermal shutters –thickness 100mm*

Intro: Still there are some savings that we will pursue in regards to the electrical load for lighting; could there be found a shutter that will allow some sunlight through but would not loose its insulative capacity? This could happen with transparent insulation confined in a synthetic shell construction. Assuming that the solar and visible transmittance of the material is 0.40 the results of the several control types are shown at Table ***11*** and Figure 41

Materials and Control types	**Setpoint**	**Light. Load - kWh**	**Heat. Load - kWh**	**Cool. Load - kWh**	**Total Load - kWh**
Translucent & Insulating Thermal Shutter					
No shutter (base case)		331.09	549.94	618.59	1499.62
Control Type_A		391.33	487.45	571.65	1450.42
Control Type_B		331.09	436.67	618.59	1386.35
Control Type_C	300W/m²	331.09	549.94	514.02	1395.05
Control Type_D	17°	331.09	406.91	619.59	1357.59
Control Type_E	17°	348.90	406.91	512.76	1268.57
Control Type_F	300W/m²	331.09	436.75	514.96	1282.80
best choice: Control Type_E	**17°**	**348.90**	**406.91**	**512.76**	**1268.57**
% variation from wooden		**17.48**	**10.95**	**-24.62**	**1.75**
% variation from base case		**-5.38**	**26.01**	**17.11**	**15.41**

*Table **11** : Annual loads of translucent and insulating planar thermal shutters*

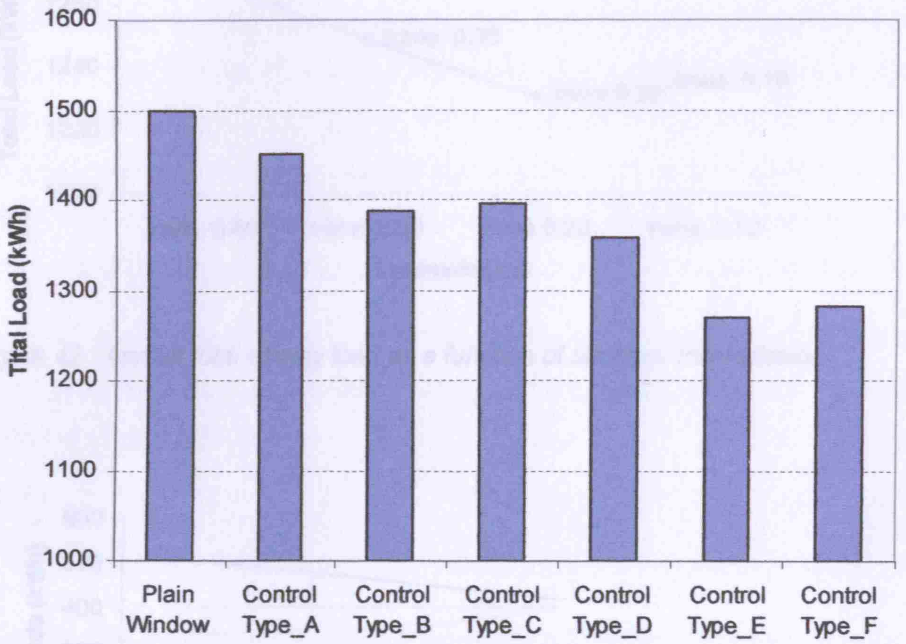

Figure 41 : Total annual loads for several control strategies of planar translucent & insulating shutters

Conclusions: The results above show that for shutters with solar and visible transmittance of 0.40 there was no reduction in total energy load from the previous system. The best control type is now E. However, we can test more transmittance values for the same control type E (see Table **12** and Figure 42).

Materials and Control types	Setpoint	Light. Load - kWh	Heat. Load - kWh	Cool. Load - kWh	Total Load - kWh
Translucent & InsulatingThermal Shutter/ Several transmission values					
Control Type_E_trans 0.40	17°	348.90	406.91	512.76	1268.57
Control Type_E_trans 0.30	17°	356.07	406.89	485.38	1248.34
Control Type_E_trans 0.20	17°	369.16	406.86	454.66	1230.68
Control Type_E_trans 0.10	17°	403.13	406.82	425.34	1235.29
best choice: trans 0.20	**17°**	**369.16**	**406.86**	**454.66**	**1230.68**
% variation from wooden shutters		**12.69**	**10.96**	**-10.50**	**4.69**
% variation from base case		**-11.50**	**26.02**	**26.50**	**17.93**

*Table **12** : Annual loads of several translucent values of planar thermal shutters.*

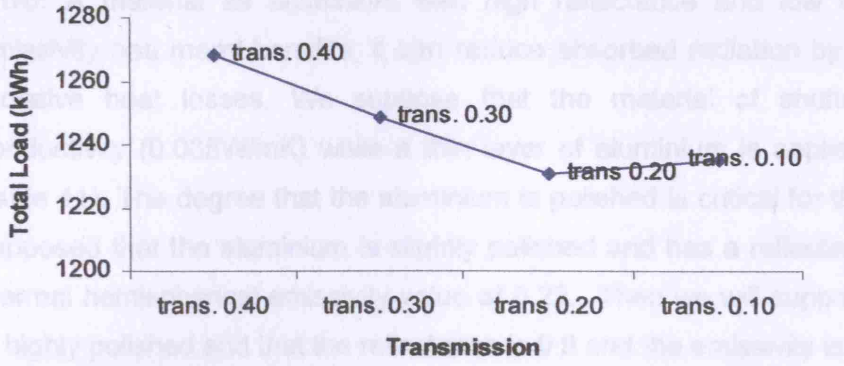

Figure 42 : Annual total energy load as a function of shutters' transmission

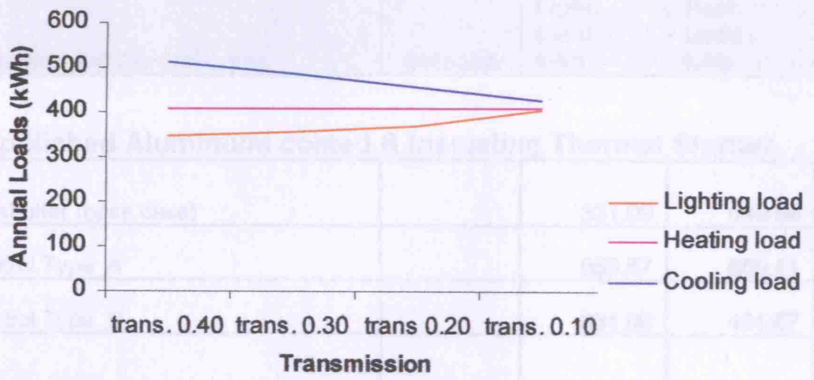

Figure 43 : Lighting, heating and cooling load as a function of shutters' transmission.

Conclusions: We managed to improve the performance of the shutters by reducing the transmittance by half, i.e.0.20. When transmittance exceeds 0.20 cooling load rises more than the natural lighting gains could compensate (see Figure 43).

Later on this study the effort will focus on reducing the lighting load by using louvered constructions that can let diffuse light in and restrain direct solar radiation. That will be done in the second part of the simulation. But before we proceed, we will modify other attributes of planar shutters, such as reflectance and emissivity.

Intro: A material as aluminium with high reflectance and low thermal hemispherical emissivity has many benefits; it can reduce absorbed radiation by reflection and reduce radiative heat losses. We suppose that the material of shutter keeps its thermal conductivity (0.035W/mK) while a thin layer of aluminium is applied at the surface (see Table 41). The degree that the aluminium is polished is critical for these values. Let's first supposed that the aluminium is slightly polished and has a reflectance value of 0.50 and thermal hemispherical emissivity value of 0.22. Then we will suppose that the aluminium is highly polished and that the reflectance is 0.9 and the emissivity is 0.10 (see Table 42).

Table ***13*** and Table ***14*** show the results of the simulations whereas the chart of *Figure 44* show a comparison of the total loads for the several control types for the polished aluminium coated shutter.

Materials and Control types	Setpoint	Light. Load - kWh	Heat. Load - kWh	Cool. Load - kWh	Total Load - kWh
Unpolished Aluminium coated & Insulating Thermal Shutter					
No shutter (base case)		331.09	549.94	618.59	1499.62
Control Type_A		955.57	659.11	438.89	2053.57
Control Type_B		331.09	431.67	618.59	1381.35
Control Type_C	300W/m²	422.53	549.94	396.69	1369.16
Control Type_D	17°	331.09	400.78	619.64	1351.52
Control Type_E	17°	532.81	400.79	399.27	1332.87
Control Type_F	300W/m²	422.64	431.74	397.28	1251.66
best choice: Control Type_F	300W/m²	422.64	431.74	397.28	1251.66
% variation from wooden shutters		0.04	5.52	3.44	3.06
% variation from base case		-27.65	21.49	35.78	16.54

*Table **13** : Annual loads of unpolished coated and insulating planar thermal shutters*

Materials and Control types	Setpoint	Light. Load - kWh	Heat. Load - kWh	Cool. Load - kWh	Total Load - kWh
Polished Aluminium coated & Insulating Thermal Shutter					
No shutter (base case)		331.09	549.94	618.59	1499.62
Control Type_A		955.57	693.84	409.70	2059.11
Control Type_B		331.09	429.83	618.59	1379.51
Control Type_C	300	421.99	549.94	377.55	1349.48
Control Type_D	17º	331.09	398.46	619.66	1349.21
Control Type_E	17º	531.56	398.46	372.45	1302.47
Control Type_F	300W/m²	422.06	429.89	378.32	1230.28
best choice: Control Type_F	**300W/m²**	**422.06**	**429.89**	**378.32**	**1230.28**
% variation from unpolished		**0.14**	**0.43**	**4.77**	**1.71**
% variation from wooden shutter		**0.17**	**5.92**	**8.05**	**4.72**
% variation from base case		**-27.48**	**21.83**	**38.84**	**17.96**

*Table **14** : Annual loads of polished coated and insulating planar thermal shutters*

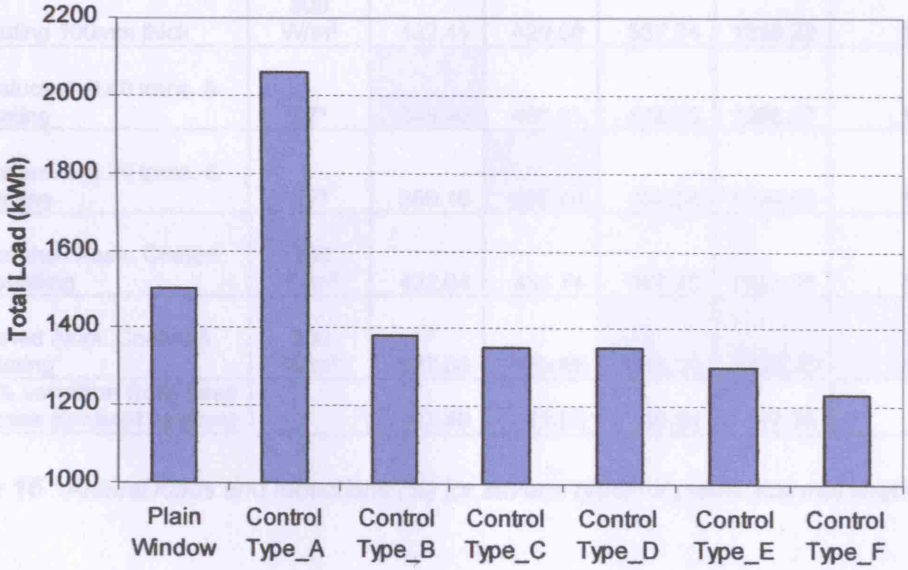

Figure 44 : Total annual loads for several control strategies of planar polished aluminium shutters

Conclusions: With unpolished aluminium the results in energy load are insignificant. By applying polished aluminium coating (problems will arise though in maintaining it such) we get the lowest results in energy load untill now. The optimal Control Type is F i.e. closing the shutters on winter nights and on summer days when cooling is on and solar radiation on window is over 300 W/m². Actually, both heating and cooling load are reduced, heating by 8%, cooling by 6% and total by 4.7% when compared with wooden shutters.

Planar shutters final results

The following

Table 15 accumulates the results of the simulations for planar shutters. For every material the control strategy that gave the best performance is presented. The charts of *Figure 45* and Figure 46 illustrate the comparison between the different systems.

Materials and Control types	**Setpoint**	**Light. Load**	**Heat. Load**	**Cool. Load**	**Total Load**	**Reduction from base case**	**Control**
	W/m^2,° W,	kWh	kWh	kWh	kWh	%	
ACCUMMULATIVE RESULTS OF PLANAR THERMAL SHUTTERS							
No shutter – base case		331.09	549.94	618.59	1499.62		
Wooden	300 W/m^2	422.80	456.94	411.45	1291.19	**13.90**	Type_F
Insulating 50mm thick	300 W/m^2	422.49	436.65	393.71	1252.84	**16.46**	Type_F
Insulating 100mm thick	300 W/m^2	422.41	429.08	387.74	1239.23	**17.36**	Type_F
Translucent- 0.40 trans. & Insulating	17°	348.90	406.91	512.76	1268.57	**15.41**	Type_E
Translucent- 0.20 trans. & Insulating	17°	369.16	406.86	454.66	1230.68	**17.93**	Type_E
Unpolished Alum. Coated & Insulating	300 W/m^2	422.64	431.74	397.28	1251.66	**16.54**	Type_F
Polished Alum. Coated & Insulating	300 W/m^2	422.06	429.89	378.32	1230.28	**17.96**	Type_F
% variation from base case (for best system)		**-27.48**	**21.83**	**38.84**	**17.96**		

*Table **15** : Annual loads and reductions (%) for several types of planar thermal shutters*

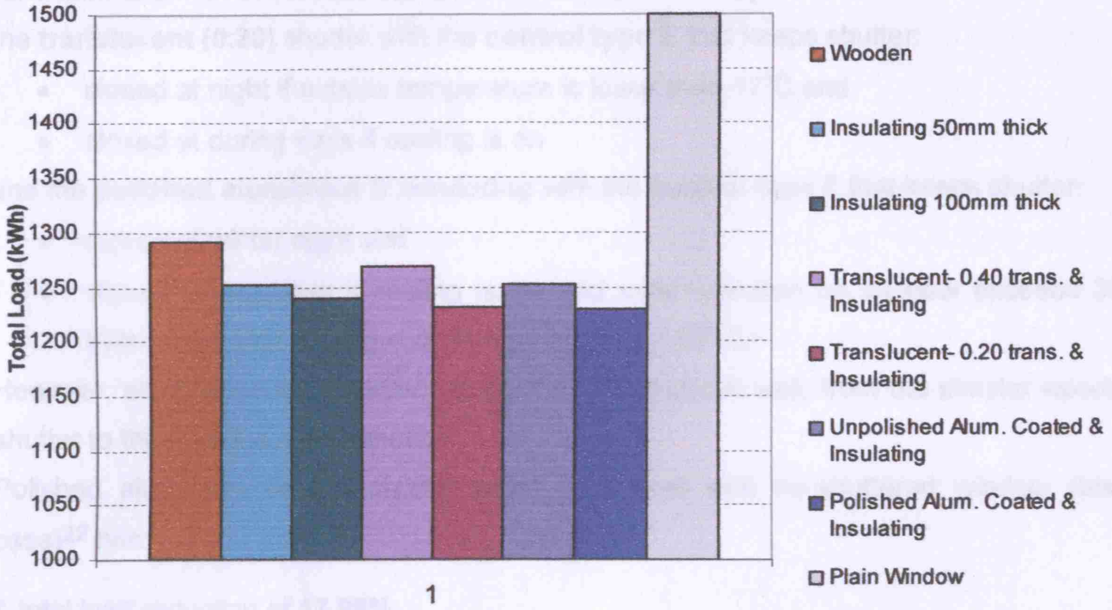

Figure 45 : Comparative chart of annual total loads of several types of planar thermal shutters

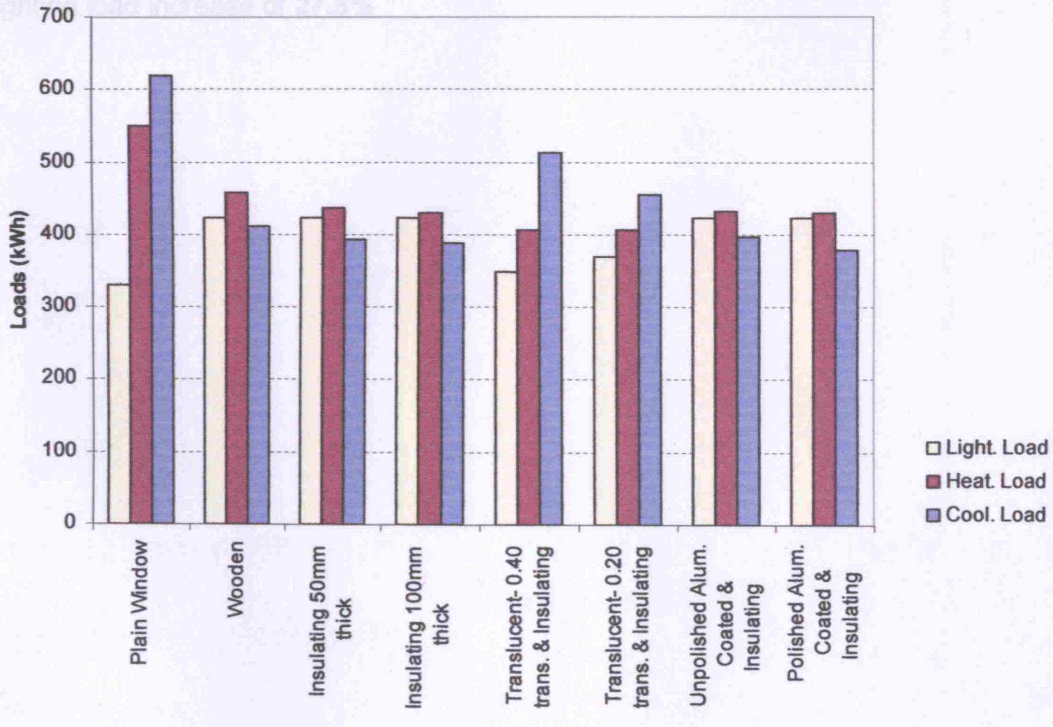

Figure 46 : Comparative chart of annual lighting, heating and cooling loads of several types of planar thermal shutters

As shown at the above charts best performance is offered by:
the **translucent (0.20)** shutter with the **control type E** that keeps shutter:

- closed at night if outside temperature is lower than 17˚C and
- closed at during days if cooling is on

and the **polished aluminium & insulating** with the **control type F** that keeps shutter:

- closed at winter night and
- closed during days if cooling is on and solar radiation on window exceeds 300 W/m².(note that cooling is on if internal temp.> 29º C)

However, all other shutters seemed to perform respectively well, from the simpler wooden shutter to the thick insulating shutter.

Polished aluminium coated shutter when compared with no-shuttered window (base case)[22] has:

A total load reduction of **17.96%,**
A cooling load reduction of **38.8%**,
A heating load reduction of **21.8%** and
A lighting load increase of **27.5%**

---

[22] *The polished aluminium & insulating is a more practicable construction than translucent insulating shutter. That is why it is considered as best case.*

Simulation Part 2 – Louvered Thermal Shutters

Simulation process of louvered shutters

In order to reduce the lighting load together with the cooling load we will test an external louvered shutter.[23] As before we will start with a simple construction with fixed wooden slats and then we will proceed to more complex control strategies and advanced materials. The initial material properties and the slats dimensions are as shown at Table 43 of Appendix A2 and its structure at Figure 47

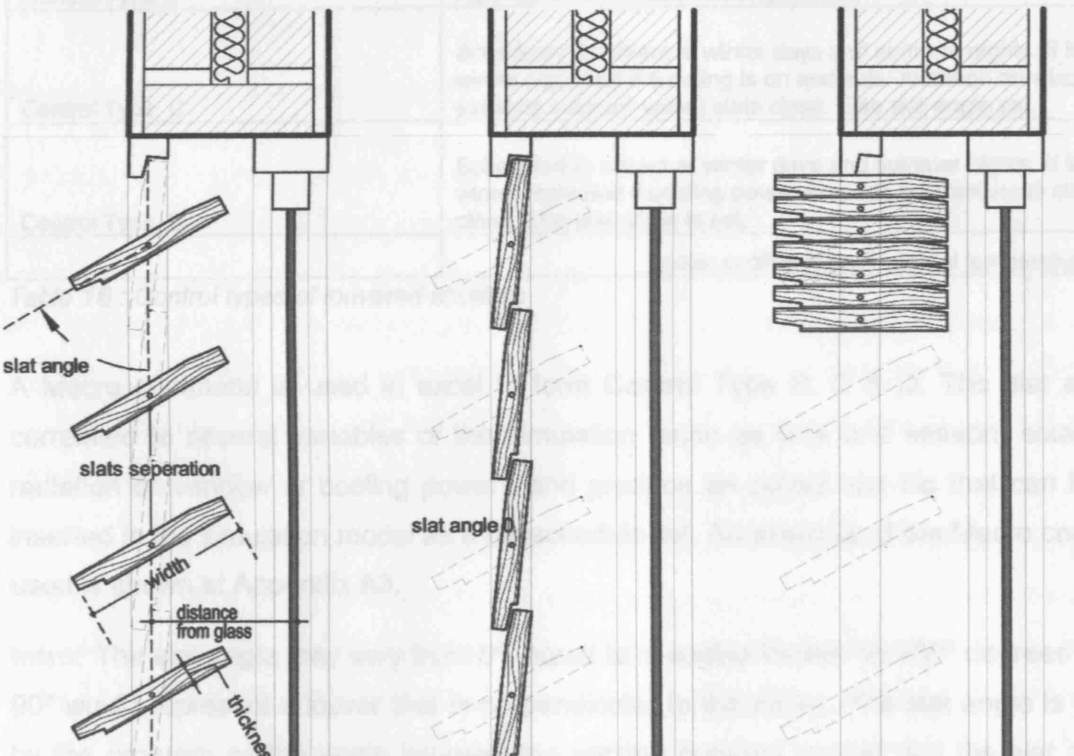

Figure 47: Detail of the shutter's slats

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[23] The louvers were modelled at Energy Plus software as exterior blinds.' It is assumed by the software that airflow through a window opening is unaffected by the presence of a shading device such as a shade or blind on the window.' (The Manual of Energy Plus, p. 632).This is a restriction of the program and there will be some aberration from real performance of louvers.

In order to judge the performance of several louvered systems we will test different control strategies. In particular the Control Types that are going to be tested are as follows (Table **16**)

Name	Description
Control Types of Louvered Shutters	
Control Type 0	Fixed slat angles
Control Type A	Scheduled to retract winter days and summer nights. Else slat angle is set.
Control Type B	Scheduled to retract winter days and summer nights. If it is winter night slats close. Else slat angle is set.
Control Type_C	Scheduled to retract at winter days and summer nights. If it is winter night and if (cooling is on and solar radiation on window exceeds setpoint value) slats close. Else slat angle set.
Control Type_D	Scheduled to retract at winter days and summer nights. If it is winter night and if cooling power exceeds setpoint value slats close. Else slat angle is set.
	note: cooling is on if internal temperature > 29°.

*Table **16** : Control types of louvered shutters*

A Macro command is used in excel to form Control Type B, C & D. The slat angle is correlated to several variables of the simulation (such as time and season, solar beam radiation on window or cooling power), and produce an output text file that can then be inserted in the simulation model as a dayschedule list. An example of the Macro command used is shown at Appendix A3.

Intro: The slat angle may vary from 0° -equal to a sealed louver- to 180° degrees (where 90° would represent a louver that is perpendicular to the pane). The slat angle is defined by the program as the angle between the glazing outward normal and the slat outward normal, pointing away from its front face (see Figure 47). The simpler louver system would have a fixed angle and no potential to retract (Control Type_0). We will first compare the performance of several fixed angles. The results of the simulations are shown at Table ***47*** of Appendix A4. The following chart (Figure 48) shows the annual heating cooling lighting and total load as slat angles vary.

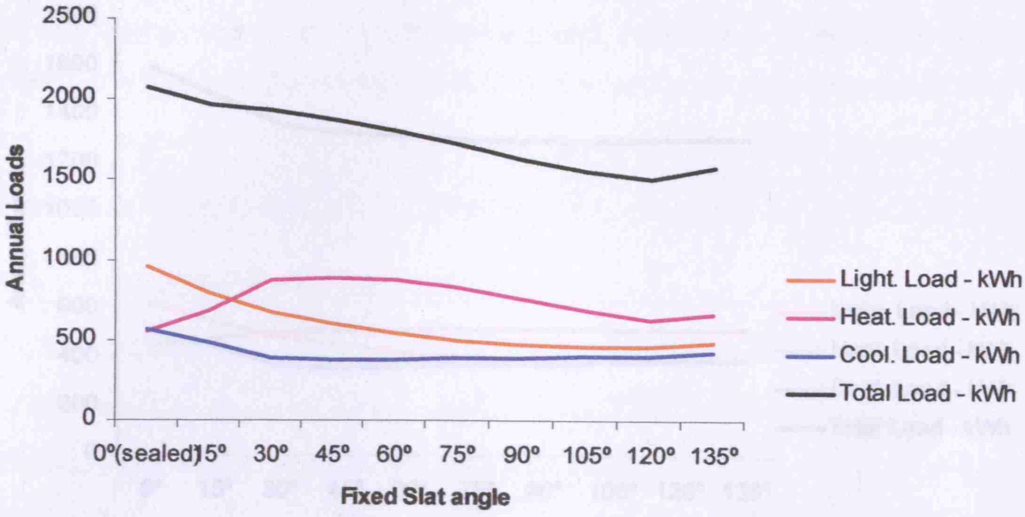


Figure 48 : Annual loads for fixed slat angles of wooden louvered shutters

Conclusions: Fixed wooden louvers on south windows seem to perform rather bad because the resulting energy loads is slightly higher than that of the plain window. An inclination of 120º gives the best results among the angles tested. However this seems logic considering the lack on heat gains during winter and the constraint of natural lighting throughout the year. When observing the Chart (Figure 48) we can see that as slat angle reaches big values the cooling load rises. For the lighting load there is an optimal point of 105º slat angle and for the heating load 120º.[24]

Intro: So, a fixed angle is not suggested. Next, we will try to eliminate the problem of loosing solar heat gains by retracting the louvers during winter days and additionally we will retract them also during summer nights to allow potentials for night cooling (Control Type A). The summer and winter period are the ones shown at Table **4**. We will test again several slat angles. The simulation results are shown at Table ***48*** of Appendix A4. The graphic representation of the results are shown at the following chart (Figure 49).

[24] *Additionally, when using the solar tool of the square one software and by observing the animation of the solar path and the shadows produced we see that an angle of the slat of 70 degrees is satisfactory to give the shading at the interior.(As we cannot present the animation in this paper characteristic snapshots of summer and winter solstice and autumnal equinox images are shown at figures 76-78 of Appendix A1)*

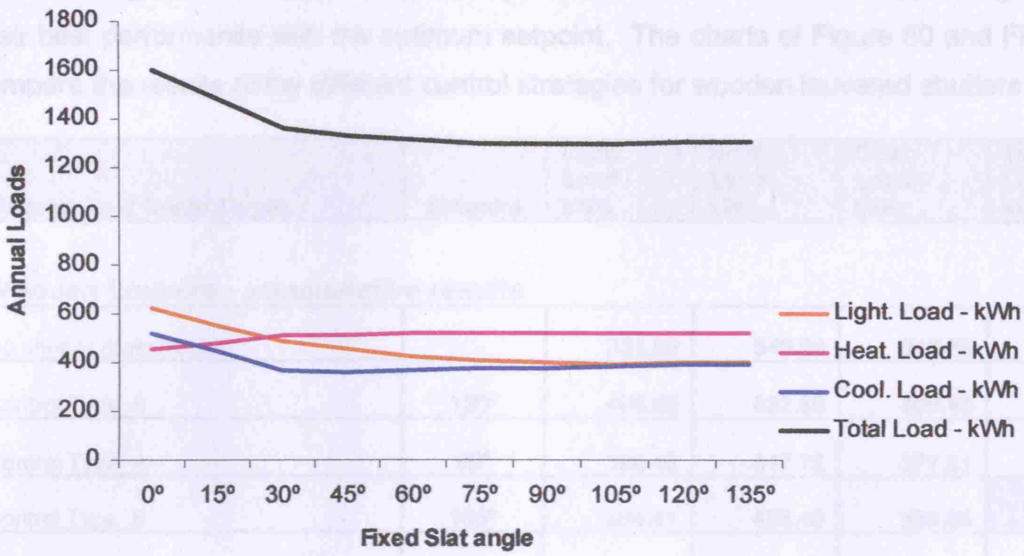


Figure 49 : The annual loads for various slat angles of wooden louvered shutters with Control Type A

Conclusions: The heating load now seems more autonomous from slat angle. Still a balance should be found between cooling load and lighting load. It seems that both 90˚ and 105˚ of slat angle perform well.

Intro: What we will try to check now is the loads reduction:

- by sealing the louvers during winter night to reduce night time heat losses (Control Type_B)
- by additionally closing them during summer days if there is high solar radiation on window while cooling is on (Control Type_C),
- or if the cooling power exceeds a set point value (Control Type D)

The optimum slat angle and set point values of each case will be found by a series of simulations that are shown at Table ***49***, Table ***50*** and Table ***51*** of the Appendix A4.[25]

---

[25] *For the Control Strategies C and D the slat angle is kept at an optimal angle of 90˚ (while the solar radiation or cooling power setpoint varies) for simplicity reasons and also because a slat angle of 90˚ degrees, is already proved have a satisfactory performance anyway.*

The following Table ***17*** accumulates the performances of the Control Types regulated at their best performance with the optimum setpoint. The charts of Figure 50 and Figure 51 compare the results of the different control strategies for wooden louvered shutters.

Materials and Control types	Setpoint	Light. Load - kWh	Heat. Load - kWh	Cool. Load - kWh	Total Load - kWh
Wooden Louvers - accumulative results					
No shutter (base case)		331.09	549.94	618.59	1499.62
Control Type_0	120º	466.05	632.86	406.43	1505.34
Control Type_A	90º	398.40	517.72	377.81	1293.93
Control Type_B	105º	394.41	456.40	380.88	1231.68
Control Type_C	450 W/m²	400.10	456.40	379.90	1236.39
Control Type_D	600 W	400.01	456.40	378.81	1235.22
best choice: Control Type_B	105º	394.41	456.40	380.88	1231.68
% variation from base case		-19.12	17.01	38.43	17.87

*Table **17** : Annual loads of wooden louvered shutters for several Control Types.*

Conclusions: By observing the above results it is obvious that closing the louvers during summer days when solar radiation on window or cooling power is high (Control Types_C and D) doesn't result in lower loads. None set point (till the highest logic) gave satisfactory results. Both energy demands for lighting and cooling would rise. Until now the best results is given by Control Type B:

- if we close the louvers during winter nights to keep the heat in, retract them during winter days to permit solar gains, retract them again during summer nights to allows night purge and to keep the slat angle at 90º during summer days to intercept the solar beam radiation.

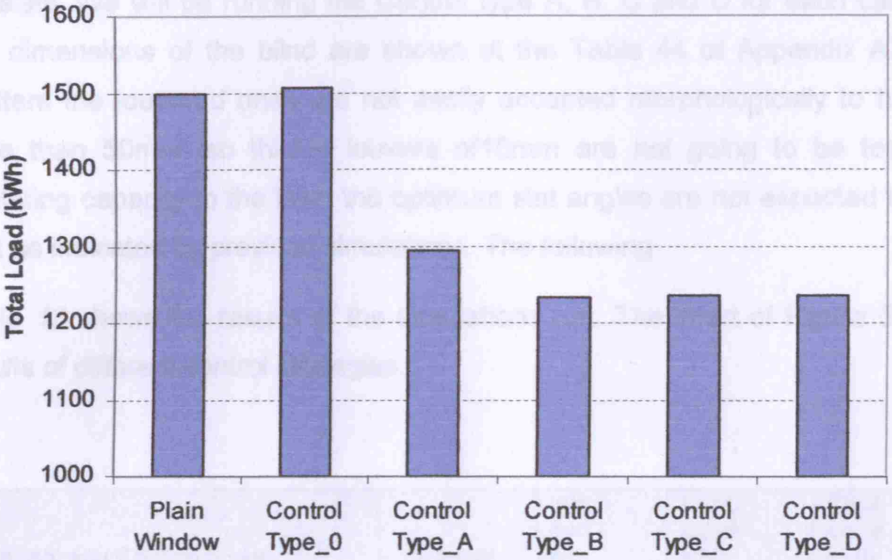


Figure 50 : Total annual loads for several Control Types of wooden louvered shutters.

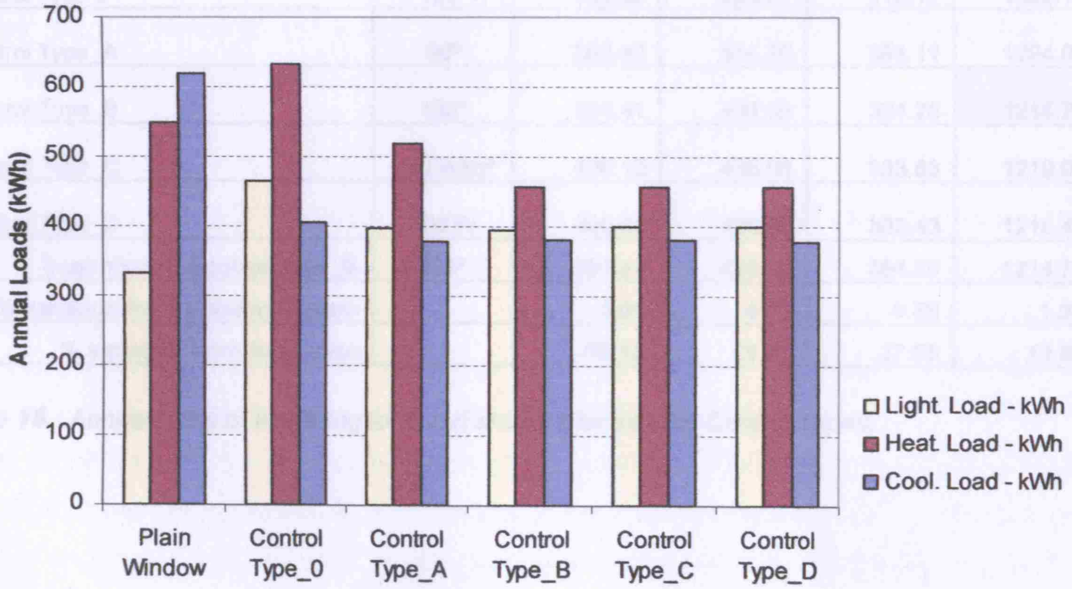


Figure 51 : Lighting, heating and cooling load for several Control Types of wooden louvered shutters.

Intro: Following, we will alter the material of the louvers and check the new energy loads. First we will alter the thermal conductivity and then the reflectance and the emissivity of the slats. We will be running the Control type A, B, C and D for each case. The material and dimensions of the blind are shown at the Table 44 of Appendix A2. Unlike planar shutters the louvered ones are not easily accepted morphologically to have a thickness more than 50mm, so thicker louvers of10mm are not going to be tested. By adding insulating capacity to the blind the optimum slat angles are not expected to alter, they are kept as indicated by previous simulations. The following

Table ***18*** shows the results of the simulations run. The chart of Figure 52 compares the results of different control strategies.

Materials and Control types	Setpoint	Light. Load - kWh	Heat. Load - kWh	Cool. Load - kWh	Total Load - kWh
Insulating Louvers – accumulative results					
No shutter (base case)		331.09	549.94	618.59	1499.62
Control Type 0	120º	466.05	623.97	412.16	1502.18
Control Type_A	90º	398.40	514.56	381.11	1294.07
Control Type_B	105º	394.41	436.06	384.25	1214.72
Control Type_C	450 W/m²	400.10	436.06	383.83	1219.98
Control Type_D	600 W	400.01	436.06	382.43	1218.49
best choice: Control Type_B	**105º**	**394.41**	**436.06**	**384.25**	**1214.72**
% variation from wooden louvers		**0.00**	**4.46**	**-0.89**	**1.38**
% variation from base case		**-19.12**	**20.71**	**37.88**	**19.00**

*Table **18** : Annual loads of insulating louvered shutters for several Control Types.*

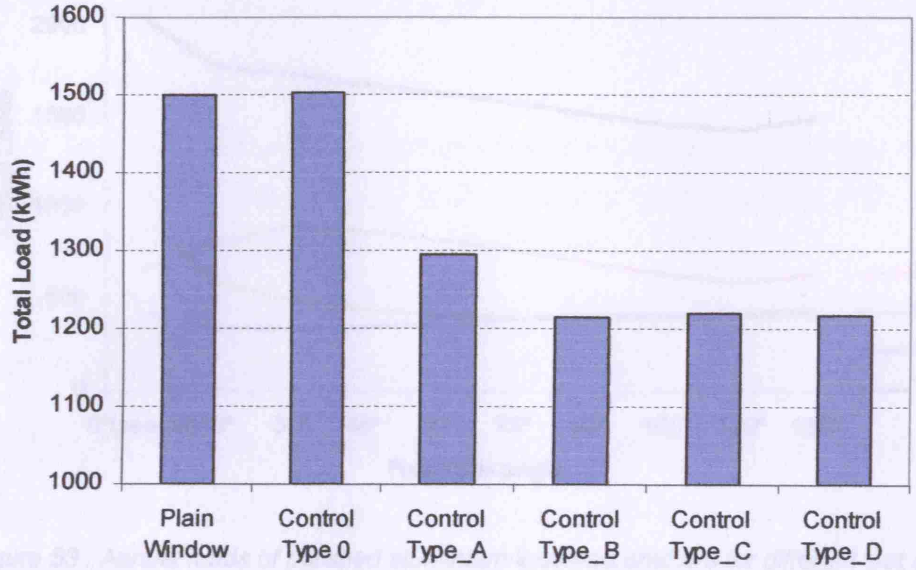


Figure 52 : Total annual loads for several Control Types of insulating louvered shutters.

Conclusions: The best Control Type performance is again Type B. The total annual energy load is reduced by 1.38% from wooden louvered shutters. Heating load is decreased by 4.5% and cooling load slightly increased (0.89%).

Intro: Following, we will test polished aluminium coated louvers that keep their insulating capability (λ=0.035 W/mK), whereas the reflectance is assumed to be 0.9 and the emissivity 0.1. The material's properties are shown at Table 45. We will test Control Types 0-D and the setpoints of the Controls are going to be redefined by a series of simulations as the particularities of the new material may give different results. Analytically, the results of the simulations for the various setpoints of the several control types are shown at Table 52 - Table ***56*** of the Appendix A. The charts at Figure 53 and Figure 54 show how heating, cooling and lighting loads vary for different slat angles for the Control Type 0 and A respectively.

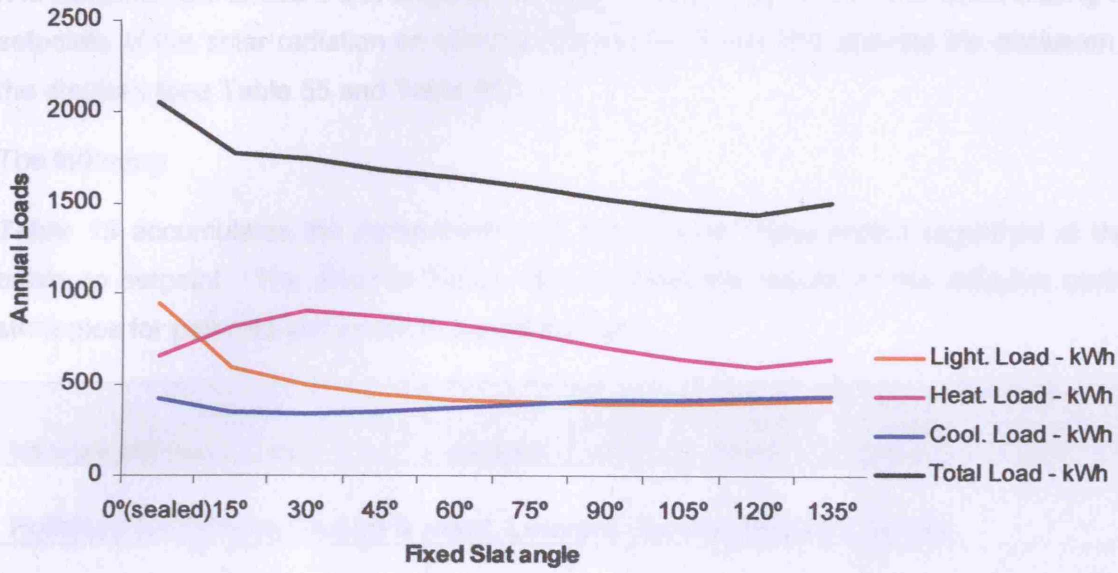


Figure 53 : Annual loads of polished aluminium louvered shutters for different slat angles of Control Type 0

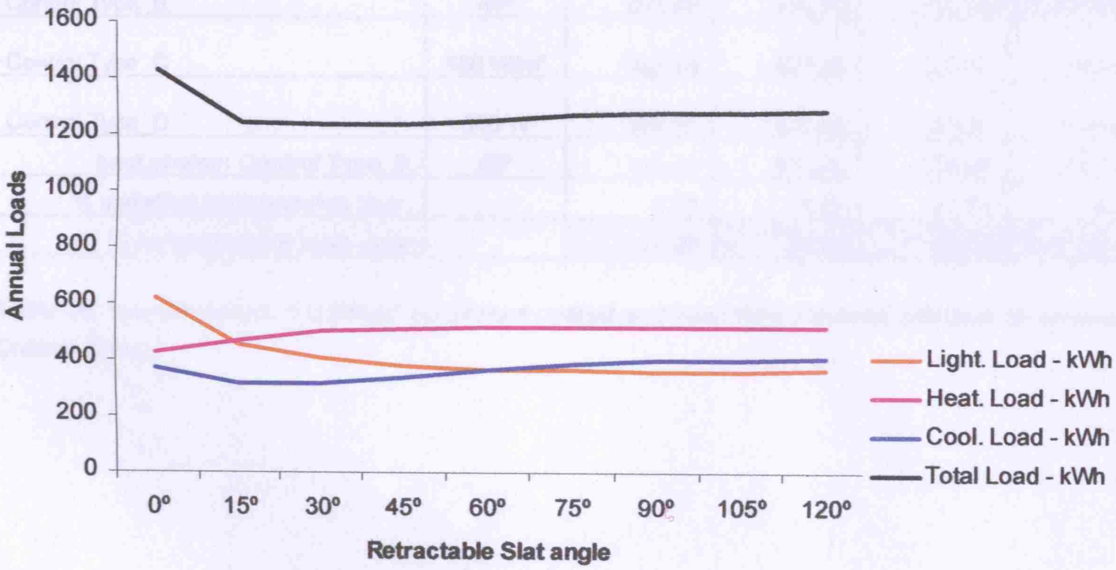


Figure 54 : Annual loads of polished aluminium louvered shutters for different slat angles of Control Type A

An interesting finding is that the optimum slat angle for Control strategy A and B is now 45˚ irrespectively with the pervious slats materials that required an optimal angle of 90˚. Slat angle 45˚ protects more from solar radiation as much radiation enters interior through various reflections.

It is sensible now to use a slat angle of 45° for the Control types C and D when testing the setpoints of the solar radiation on window the cooling power that activate the occlusion of the shutters (see Table 55 and Table ***56***)

The following

Table 19 accumulates the performances of the Control Types tested regulated at their optimum setpoint. The chart of Figure 55 compares the results of the different control strategies for polished aluminium louvered shutters.

Materials and Control types	Setpoint	Light. Load - kWh	Heat. Load - kWh	Cool. Load - kWh	Total Load - kWh
Polished Aluminium Coated & Insul. Louvers - accummulative results					
No shutter (base case)		331.09	549.94	618.59	1499.62
Control Type 0	120º	403.51	601.85	422.80	1428.15
Control Type_A	45º	381.33	513.22	336.68	1231.23
Control Type_B	45º	381.48	430.26	336.49	1148.23
Control Type_C	450 W/m²	383.18	430.26	336.50	1149.94
Control Type_D	500 W	382.85	430.26	336.54	1149.65
best choice: Control Type_B	**45º**	**381.48**	**430.26**	**336.49**	**1148.23**
% variation from wooden louv.		**3.28**	**5.73**	**11.65**	**6.78**
% variation from base case		**-15.22**	**21.76**	**45.60**	**23.43**

*Table **19** : Annual loads of polished Aluminium coated and insulating louvered shutters for several Control Types.*

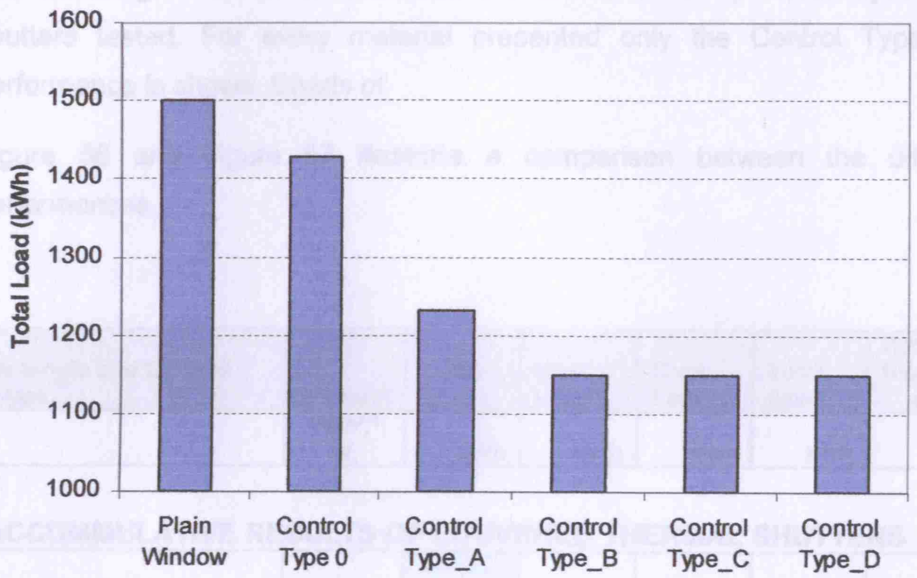


Figure 55 : Total annual loads of several control strategies of polished aluminium coated & insulating louvered shutters.

Conclusions: The best performance is offered by Control Type B that:

- closes the louvers during winter nights to keep the heat in, retracts them during winter days to permit solar gains, retracts them again during summer nights to allows night purge and keeps the slat angle 45˚ during summer days to intercept the solar beam radiation.

Louvered shutters final results

The following Table ***20*** accumulates the results of the previous systems of louvered shutters tested. For every material presented only the Control Type with the best performance is shown. Charts of

Figure 56 and Figure 57 illustrate a comparison between the different systems' performances.

Materials and Control types	Setpoint	Light. Load	Heat. Load	Cool. Load	Total Load	Reduction from base case	Control
	W/m²,° W,	kWh	kWh	kWh	kWh	%	
ACCUMMULATIVE RESULTS OF LOUVERED THERMAL SHUTTERS							
No shutter – base case		331.09	549.94	618.59	1499.62		
Wooden louvers	105°	394.41	456.40	380.88	1231.68	**17.87**	Type_B
Insulating louvers	105	394.41	436.06	384.25	1214.72	**19.00**	Type_B
Polished Alum. coated & Insulating louvers	45°	381.48	430.26	336.49	1148.23	**23.43**	Type_B
% variation from base case		**-15.22**	**21.76**	**45.60**	**23.43**		

Table 20 : Annual loads of different systems of louvered shutters.

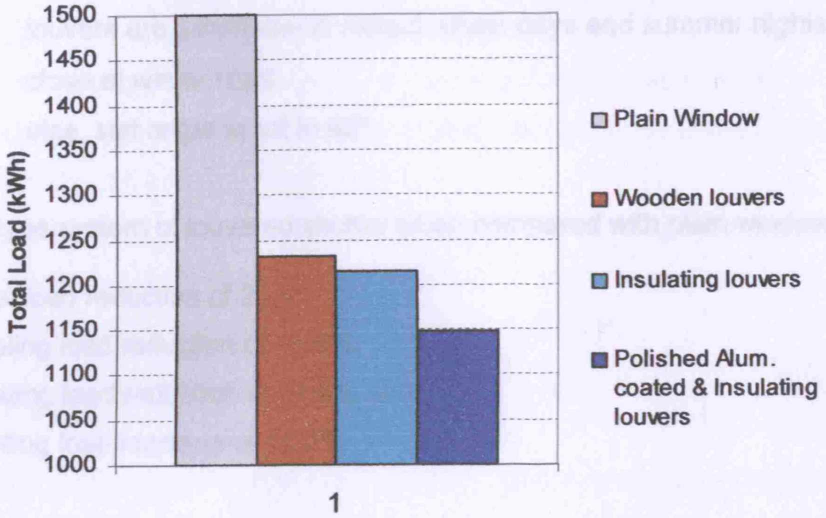


Figure 56 : Total loads of several systems of louvered shutter

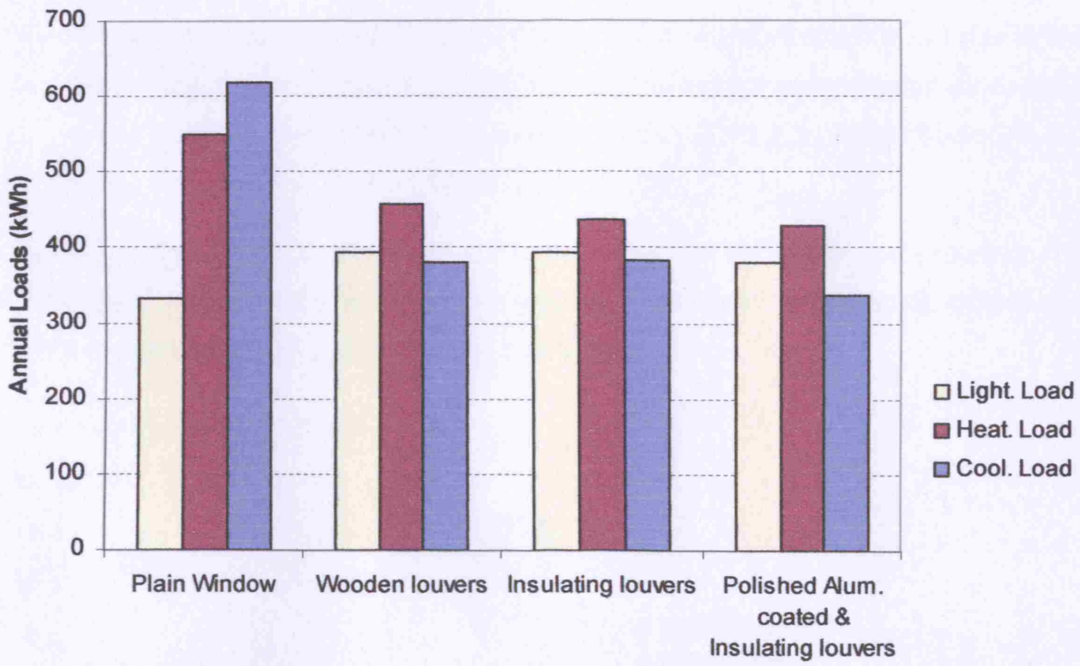


Figure 57 : Annual loads of several systems of louvered shutters

As shown at the above charts best performance was achieved by the **polished aluminium louvered shutter** with insulating capability controlled by the **Control Type B** that:

- louvers are scheduled to retract winter days and summer nights.
- close at winter night.
- else, slat angle is set to 45°.

This type system of louvered shutter when compared with plain window (base case) has:

A total load reduction of **23.4%**,
A cooling load reduction of **45.6%**,
A heating load reduction of **21.8%** and
A lighting load increase of **15.2%**

Analysing and Examining Parameters

Until now we prescribed shutter systems that could save significant amount of energy load. However, questions like the following arise:

How much should a shutter cost to make its purchase and application cost effective?

How would parameters of buildings such as window-to-floor ratio windows orientation and glazing material influence the results?

What would the use of shutters influence the thermal comfort for free running buildings?

The shutter systems involved in the following analysis are assessed at their best control type performance, as indicated at the previous chapter.

Cost analysis

We are going to perform a cost analysis for the shutter system that showed the best performance i.e. the aluminium insulating louvered shutter and for the simpler one, i.e the wooden planar shutter that would probably have the lower cost. When we calculate the cost we will be using the consumption value according to the efficiency of heating, cooling and lighting that is assumed as follows:

- the heating is supposed to be electric so it would be 100% efficient. In this case the consumption is equal to load.
- The electric lighting is 100% efficient as well. So, the consumption is equal to load.
- for cooling the cooler is assumed to be a typical vapour compression air-to-air heat pump with a system coefficient of performance (COP) 2,3 (Cibse Guide B2, 2001, table 4.7, pp. 4-51). So it would be 230% efficient.

In this case, the energy consumption of the two systems are formed as shown on Table ***21***. The chart of Figure 58 illustrates the comparison between energy loads reduction and final energy consumptions savings for the two systems.

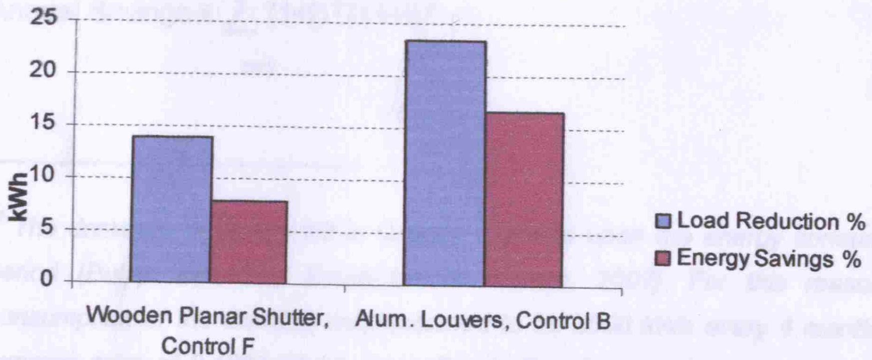


Figure 58 : Energy load reduction % and consumption savings % for planar wooden and aluminium louvered shutters

Materials and Control types	Light. Load kWh	Heat. Load kWh	Cool. Load kWh	Total Load kWh	Load Reduction %	Annual Consumption kWh	Annual Savings kWh	Energy Savings %	Savings per shutter area €/m²	Maximum Profitable Investment €/m²
No-shutter, Wooden Planar Shutter and Aluminium Louvered Shutter										
No shutter	331.09	549.94	618.59	1499.62		1149.98				
Wooden Planar Shutter, Control F	422.80	456.94	411.45	1291.19	13.90	1058.63	91.35	7.94	3.11	38.56
Alum. Louvers, Control B	381.48	430.26	336.49	1148.23	23.43	958.04	191.94	16.69	6.54	81.02

*Table **21** : Annual energy consumption, savings and profits of various shutter systems*

The electricity cost in Greece for domestic use is calculated[26] at 0.1022 €/kWh (0.0694 £/kW).

- The Alum. Insulating Louvered Shutter would give annual savings of:
  191.94 x 0.1022 = 19.62€ (13.32 £)
- The simple Wooden Shutter would give annual savings of:
  91.13 x 0.1022 = 9.31 € (6.32£)

If we want a payback time of the initial investment to be less than 20 years time (that is the expected lifetime of the building before refurbishment) then we can find the highest initial cost of shutter that would made it a rational investment.

If we take into account that fuel prices fluctuate and the fact that people regard costs and benefits of the future as being of less importance than costs and benefits of today then we should discount the energy savings of each shutter system for the 20 years period. The discounted savings for 20 years period are found by the following equation:

$$\text{Annual Savings} \times \sum_{t=1}^{t=20} (1+f)^{t} / (1+i)^{t}$$

---

[26] *The domestic electricity bill in Greece depends upon the energy consumption over a 4-month period (Public Electricity Enterprise of Greece, 2007). For this reason the total electricity consumption of the dwelling was assumed to be 2000 kWh every 4 months. That would give an average price of 0.1022 €/kWh according to the charges. Also the current (25/07/007) exchange rate of euro to English pounds is 0.679.*

The i (discount rate) is assumed to be 10% . So, i = 0.10

The f (fuel inflation) will be calculated as the average electricity inflation of the latest 10 years for Greece. The source for the electricity prices is the Department for Business, Enterprise and Regulatory Reform (2007), see Table **22**. So, f = 0.0473

	Cost of electricity in Greece for the last 10 years (pence/kWh)										
year	'96	'97	'98	'99	'00	'01	'02	'03	'04	'05	'06
pence/kWhr	7.35	6.25	5.98	5.57	4.68	4.87	5.12	5.85	5.83	6.17	6.94
annual changes %		5.25	4.98	4.57	3.68	3.87	4.12	4.85	4.83	5.17	5.94
Average annual change %											**4.73**

*Table **22** : Annual cost and changes of electricity price in Greece.*

We can now calculate the discount factor:

$$\sum_{t=1}^{t=20} (1+0.047)^{t} / (1+0.10)^{t} = 12.39$$

Over 20-year period:

Aluminium Louvered Shutter Savings x 12.39 = 19.62 x 12.39 = 243.05 € (165.03 £)

Wooden Planar Shutter Savings x 12.39 = 9.31 x 12.39 = 115.40 € (78.36 £)

Taking into consideration that the shutter will have to cover a window area of 3.00 m², the net present cost analysis shows that in order to have a payback time of less than 20 years:

- The **Aluminium & Insulating Louvered Shutter** offering energy savings of **16.7%** should cost less than 243.05 € (£ 165.03), i.e. **81.0 €/m²** (£ 55.0).
- The **Wooden Planar Shutter** offering energy savings of **7.9%** should cost less than 115.40 € (£ 78.36), i.e. **38.5 €/m²** (£ 26.12)

Window-to-floor Ratio parameter

Following, we will examine some parameters that influence the results of the energy consumption and profitable investment.

At the following calculations we will be using the terms:

- 'Savings per Shutter Area' (€/m²): as the annual energy consumption for the room without shutters minus the energy consumption of the room with shutters, per window area.
- 'Maximum Profitable Investment per Shutter Area' (€/m²): as the value that would give as a 20 year payback period when the savings are discounted according to the Net Present Cost calculation.

By altering the window-to-floor ratio the two shutter systems (wooden planar and aluminium louvered) were examined again by a series of simulations and their results are gathered at Table **57** and Table **58** of Appendix A4. The following charts show the fluctuation of energy load and the savings per window area as a function of window-to-floor ratio, for both planar wooden shutters and aluminium louvered shutters (Figure 59 and Figure 60).

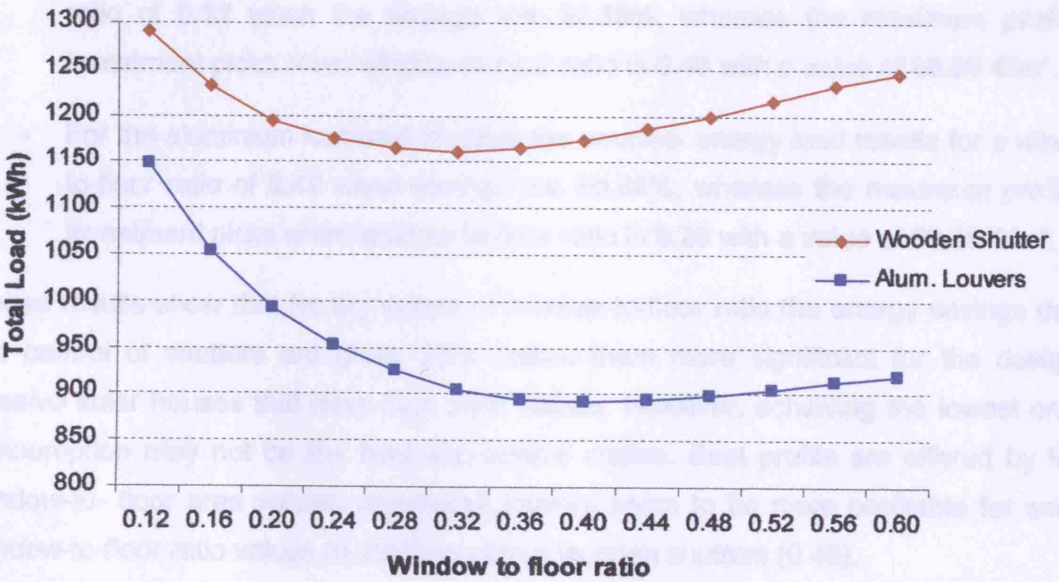


Figure 59: Total annual energy load as a function of window to floor ratio.

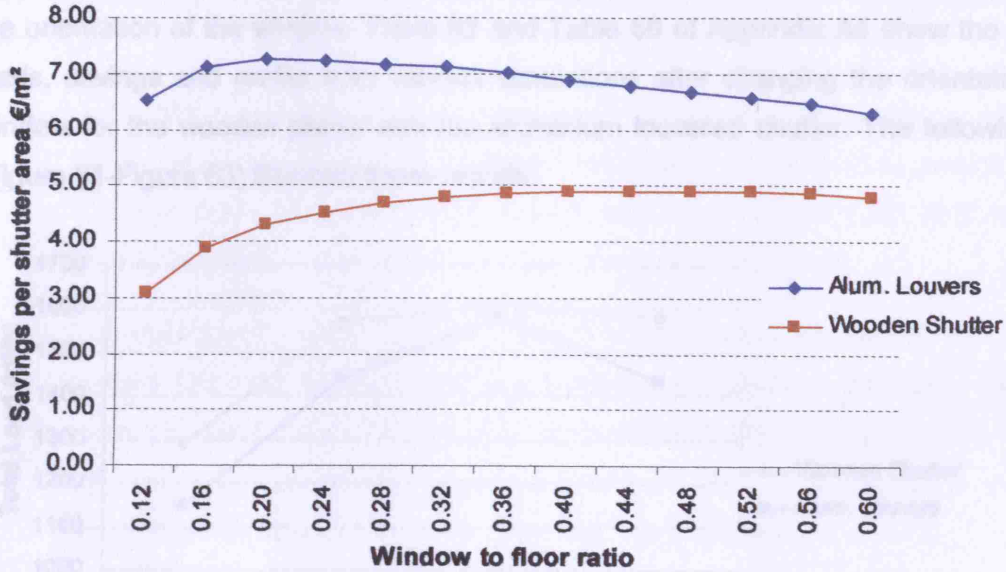


Figure 60: Annual savings per shutter area as a function of window to floor ratio for the planar wooden shutters.

The study showed that:

- For planar wooden shutters the smallest energy load results for a window-to-floor ratio of **0.32** when the savings are **30.36%**, whereas the maximum profitable investment picks when window-to-floor ratio is **0.48** with a value of **60.80 €/m²**.
- For the aluminium louvered shutters the smallest energy load results for a window-to-floor ratio of **0.40** when savings are **50.88%**, whereas the maximum profitable investment picks when window-to-floor ratio is **0.20** with a value of **89.90 €/m²**.

These results show that for big values of window-to-floor ratio the energy savings due to the control of shutters are great. This makes them more significant for the design of passive solar houses that have high such values. However, achieving the lowest energy consumption may not be the best economical choice. Best profits are offered by lower window-to- floor area values. Aluminium louvers seem to be more profitable for smaller window-to-floor ratio values (0.20) than planar wooden shutters (0.48).

Orientation parameter

Another factor that influences the energy savings by controlling thermal shutters would be the orientation of the window. Table **59** and Table **60** of Appendix A4 show the results in loads, savings and profits from various simulations after changing the orientation of the window for the wooden planar and the aluminium louvered shutter. The following charts (Figure 61-Figure 63) illustrate those results.

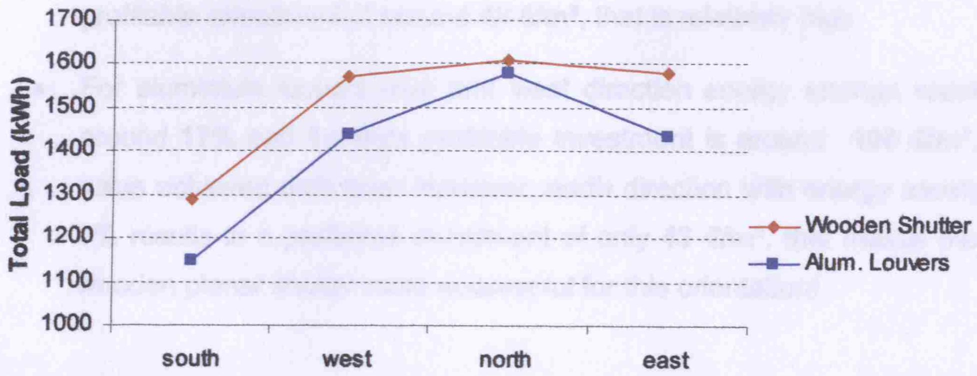


Figure 61: Total annual loads as a function of orientation for the wooden planar and the aluminium louvered shutter.

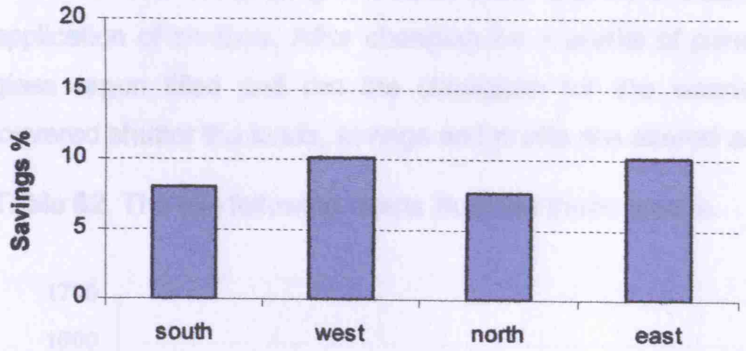


Figure 62: Savings % as a function of orientation for the planar wooden shutter.

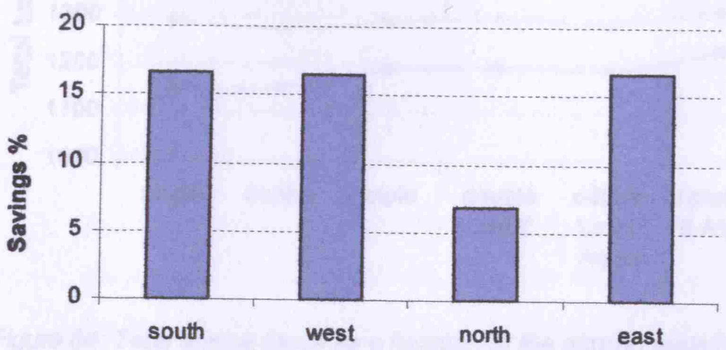


Figure 63: Savings % as a function of orientation for the aluminium louvered shutter.

The total loads are bigger for east and west than for south orientation and pick for the north. Savings are much bigger for east and west direction and much less for north, which makes shutters a much more profitable investment when applied at east and west. In particular,

- For planar wooden shutters east and west direction energy savings reach a value of around **10%** and the max profitable investment on shutters is around **63 €/m²**, whereas north direction energy savings are less, around **7.5%** that result in a profitable investment of around **48 €/m²**, that is relatively high.
- For aluminium louvers east and west direction energy savings reach a value of around **17%** and the max profitable investment is around **100 €/m²**, the highest value achieved until now. However, north direction with energy savings of around **7%** results in a profitable investment of only **43 €/m²**, that makes the choice of a wooden planar shutter more successful for this orientation!

The glazing material parameter

The material of the glazing is another factor that we should take under consideration at the application of shutters. After changing the material of panes into low-e double and triple glass argon filled and run the simulation for the wooden planar and the aluminium louvered shutter the loads, savings and profits are altered as shown at Table **61** and

Table 62. The two following charts illustrate those results.

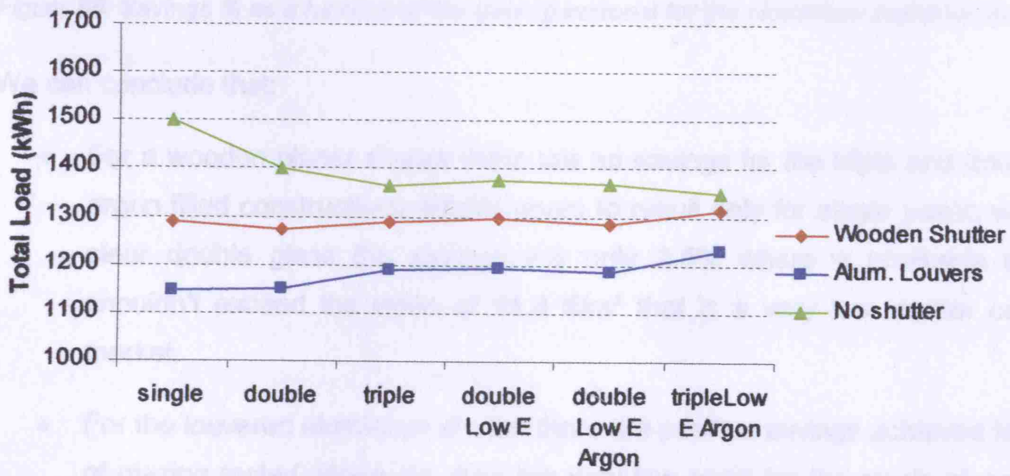


Figure 64: Total annual loads as a function of the glazing material for the planar wooden and the aluminium louvered shutter.

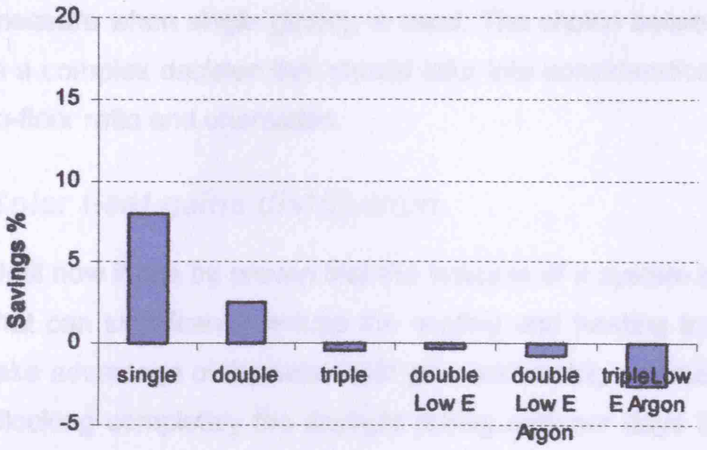


Figure 65: Savings % as a function of the glazing material for the wooden planar shutter.

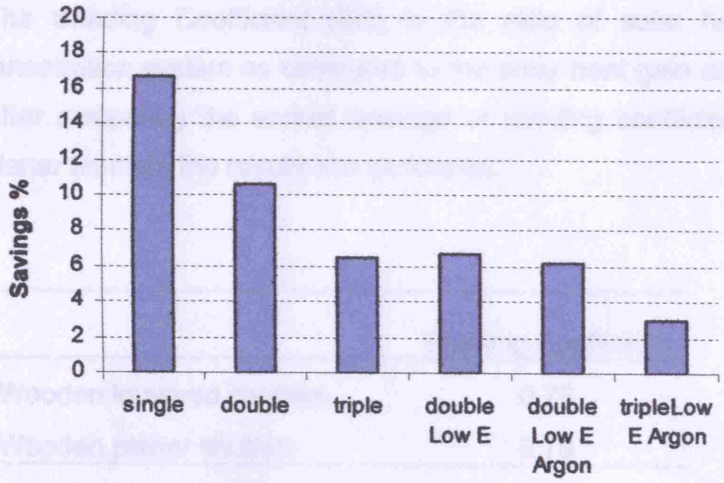


Figure 66: Savings % as a function of the glazing material for the aluminium louvered shutter.

We can conclude that:

- For a wooden planar shutter there are no savings for the triple and double Low E argon filled constructions. Profits seem to result only for single panes whereas for clear double glass the savings are only **2.5%** where a profitable investment shouldn't exceed the value of **11.3 €/m²** that is a very low shutter cost for the market.
- For the louvered aluminium shutter there are positive savings achieved for all types of glazing tested. However, they are very low apart for the single glass, whereas for the double glass a **3.87%** savings gives a profitable investment of **48 €/m²** that is a low cost for a sophisticated shutter construction.

The previous analysis proved that for south orientation shutters are a profitable retrofit measure when single glazing is used. The choice between high-tech glazing and shutters is a complex decision that should take into consideration all other parameters as window-to-floor ratio and orientation.

Solar heat gains distribution

Until now it has be proven that the success of a system is mainly ought to the solar control that can significantly reduce the cooling and heating load. During winter time we aim to take advantage of the solar heat gain and during summer time to intercept solar radiation. Blocking completely the daylight during summer days the lighting load would rise. The right strategy would permit good visual conditions without excess of light because light eventually transforms into heat.

The Shading Coefficient (SC) is the ratio of solar heat gain admitted through the fenestration system as compared to the solar heat gain admitted through 1/8" clear glass. After computing the annual average of shading coefficient of the wooden louvered and planar shutters the results are as follows:

	Shading Coefficient
Wooden louvered shutters	0.75
Wooden planar shutters	0.79

The control strategies that produced these results were the ones that have proved to result in the lowest loads. In particular:

- the wooden planar shutter is: On at winter nights and during days if cooling is on and solar radiation on window exceeds a setpoint value (300 W/m²). (Control F)
- the wooden louvered shutter is: Scheduled to retract winter days and summer nights, if it is winter night slats close, else slat angle is set (105°). (Control B)

The diagrams below show the hourly values of the SC distribution for the louvered (Figure 67) and the wooden shutters (Figure 68).

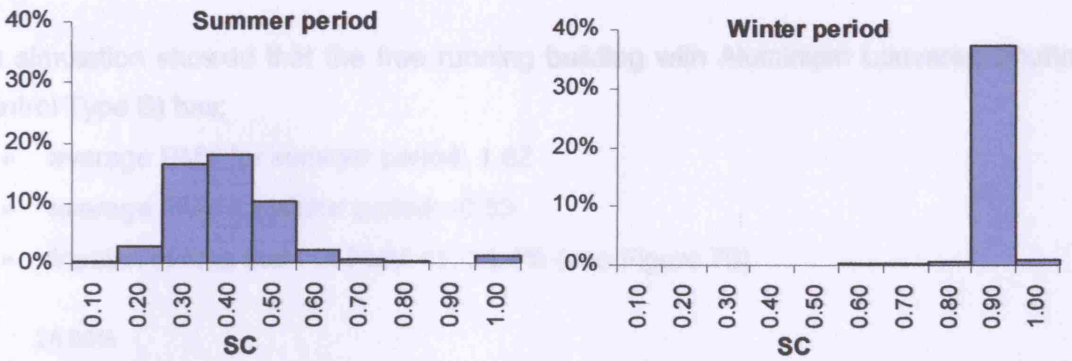


Figure 67: Distribution of hourly values of shading coefficient for wooden louvers for summer period (1/5-30/9) and winter period (1/10-41/4)

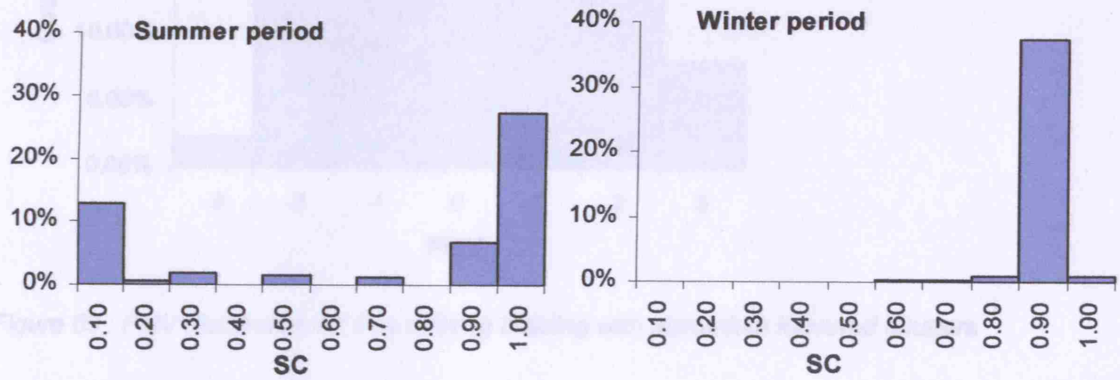


Figure 68: Distribution of hourly values of shading coefficient for wooden planar shutters for summer period (1/5-30/9) and winter period (1/10-41/4)

Although there is not much difference on the annual average of the SC between the two systems the distribution during summer period for the louvered shutters accumulates at smaller values, between 0.30-0.50 when the planar shutters accumulates at 0.90-1.00. That gives the advantage to the louvered system to restrict extreme values of solar heat gain that would cause overheat without negating a portion of light to pass through and illuminate the space.

Assessment of thermal comfort

At this point we are going to examine the benefits on thermal comfort when using shutters. We will compare the best system (aluminium louvers with insulation) with a window with no shutters for a free running building. In particular we will compare the resulting PMV (Predicted Mean Vote of heat balance approach of Prof. O. Fanger) for each case.

Two people are assumed to be seated quiet in proximity to the window and thus have a metabolic rate of 1.00 MET. Their clothing thermal resistance is assumed to be 0.75 clo, for wearing shirts, trousers, socks and shoes (Cibse Guide A, 2006, table 1.2, pp.1-5).

The simulation showed that the free running building with Aluminium Louvered Shutters (Control Type B) has:

- average PMV for summer period: 1.62
- average PMV for winter period: -0.83
- fraction of time that -1< PMV <1: 34.4% (see Figure 70)

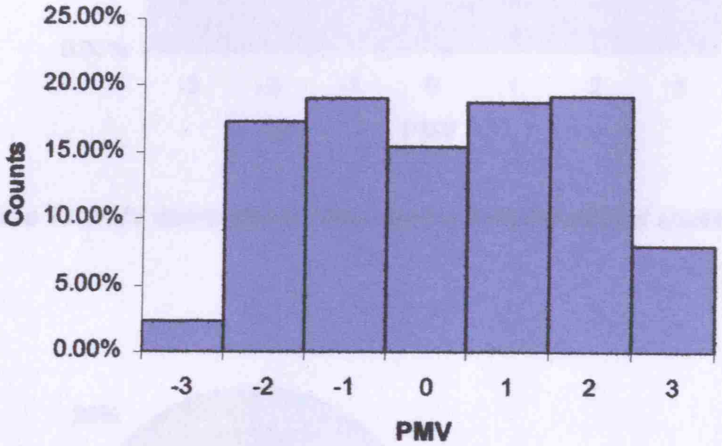


Figure 69 : PMV distribution for free running building with aluminium louvered shutters

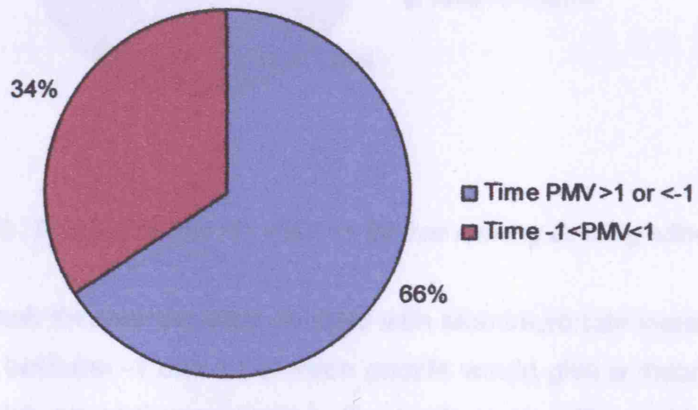


Figure 70 : Fraction of time -1< PMV <1 for free running building with aluminium louvered shutters

The simulation also showed that the free running building without shutters has:

- average PMV for summer period: 2.02
- average PMV for winter period: -1.18
- Fraction of time that -1<PMV<1: 25.7 % (see Figure 72)

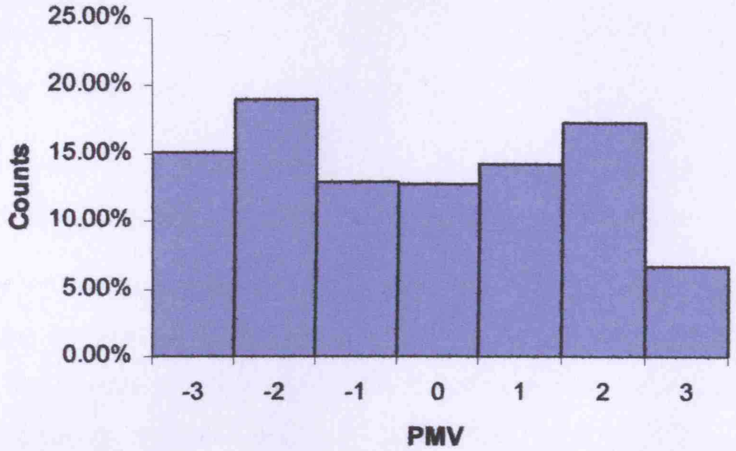


Figure 71: PMV distribution for free running building without shutters

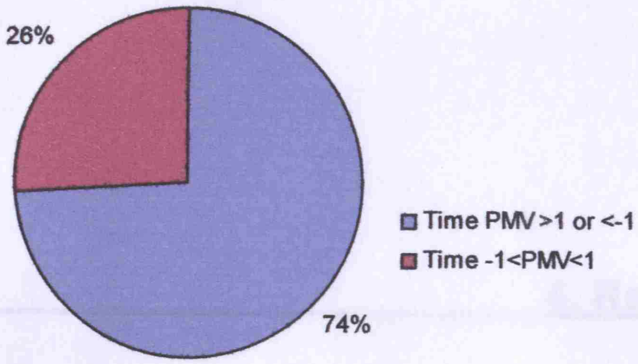


Figure 72 : Fraction of time -1< PMV <1 for free running building without shutters

As a result thermal louvered shutters with aluminium can increase by 8.7% the time when PMV is between -1 and 1 i.e. when people would give a mean vote between slightly cool and slightly warm thermal feeling. (In strictly air-condition environment the comfort zone is considered to be between -0.5 and 0.5 PMV, however in a free-running building the thermal tolerance is elastic.)

As already mentioned a complete study should include a real case experiment. The following is an experiment accomplished at the restricted time period of this dissertation, and was carried out after my guidance thanks to the kind collaboration of the inhabitants of the building. It mainly has an auxiliary character for the simulation part of the study, and for that it will be described in brief.

4. Real Case Experiment

The context

Description of the experiment

Results

Conclusions from the experiment

4. Real Case Experiment

The context

The tests that follow concern the recording of thermal performance of 2 shutters each belonging to a different room of the same accommodation.

The rooms belong to a typical construction of the '70s of an apartment in Heraklion, at the south of Greece. They belong to the third and top floor of an accommodation block, found at the centre of the town. Their dimensions are 3.00 x 3.00m. The description of their construction and plan of the rooms is shown at Figure 73

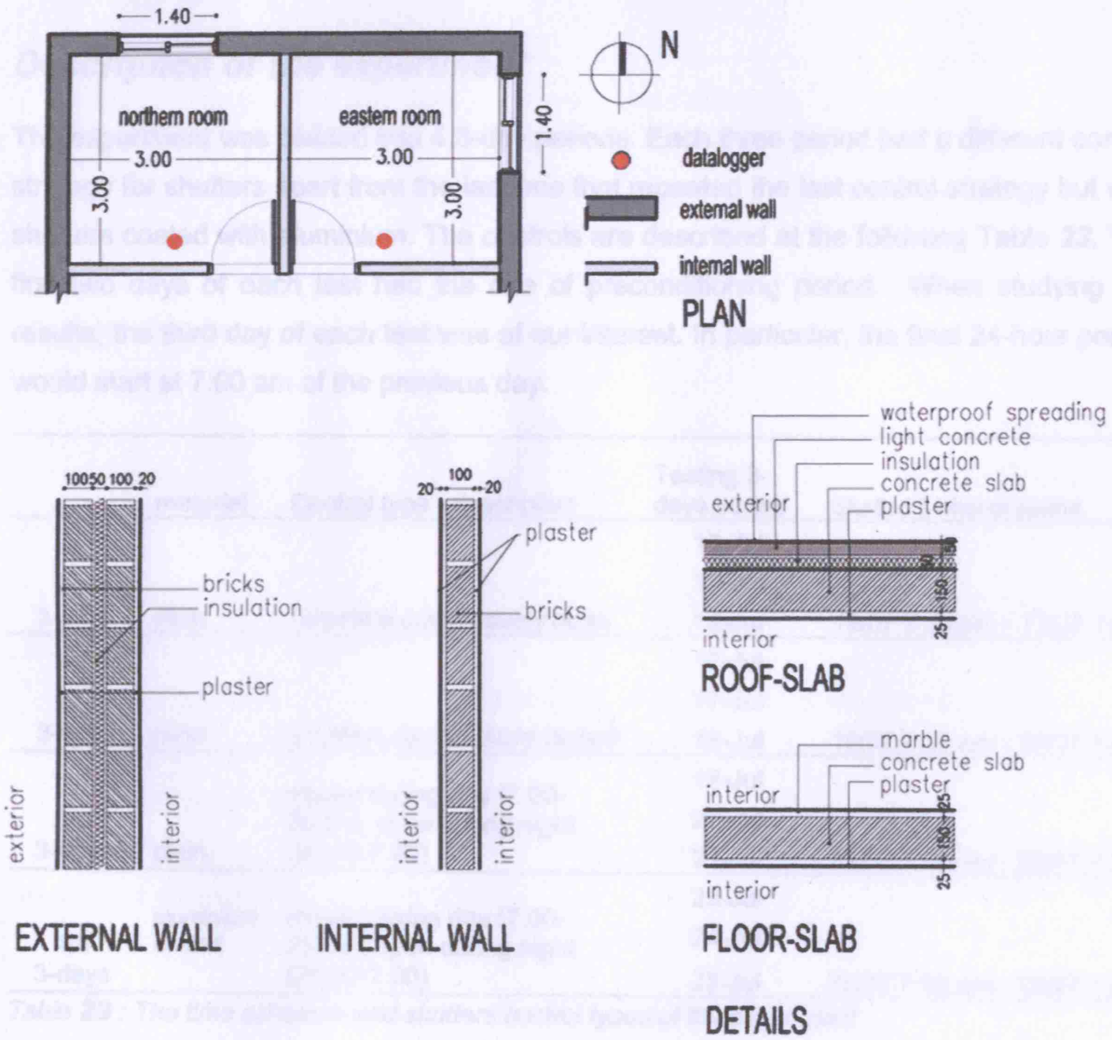


Figure 73 : The plan of the rooms and the details of their construction

Each window consists of two single glass panes that slide at each other. The shutters are plastic dark brown 50mm thick with hollow core. When they close they don't seal firmly. Two data loggers were located in each room. The external weather data was taken from The Weather Underground, Inc. [Available from: <http://www.wunderground.com>. Assessed on 15/07/2007]

The aim of the experiment is to investigate whether the right control the shutters can result in improved internal thermal conditions during the overheated period. In particular:
Can thermal conditions be improved by closing the shutters during the day? How much can internal temperature be reduced?
Are there potentials in improving shutters performance by altering the properties of their material?

Description of the experiment

The experiment was divided into 4 3-day periods. Each three period had a different control strategy for shutters apart from the last one that repeated the last control strategy but with shutters coated with aluminium. The controls are described at the following Table **23**. The first two days of each test had the role of preconditioning period. When studying the results, the third day of each test was of our interest. In particular, the final 24-hour period would start at 7.00 am of the previous day.

	material	Control type - description	Testing 3-days period	Studied 24-hours period
1st 3-days	plain	shutters continuously open	10-Jul 11-Jul 12-Jul	12/07 7.00 am - 13/07 7.00am
2nd 3-days	plain	shutters continuously closed	16-Jul 17-Jul 18-Jul	18/07 7.00 am - 19/07 7.00am
3rd 3-days	plain	closed during day (7.00-20.00), open during night (20.00-7.00)	19-Jul 20-Jul 21-Jul	21/07 7.00 am - 22/07 7.00am
4th 3-days	aluminium coated	closed during day (7.00-20.00), open during night (20.00-7.00)	23-Jul 24-Jul 25-Jul	25/07 7.00 am - 26/07 7.00am

*Table **23** : The time schedule and shutters control types of the experiment*

It is worth mentioning that during the whole experiment:

- the rooms were unoccupied
- the doors of the rooms were kept closed
- the glass panes of the windows were kept closed during the day (7.00am-20.00pm) and open at night (20.00pm-7.00am)

The measurement took place during July with clear sky and hot weather conditions. General the weather characteristics for each studied period are shown at

Table 24. During the days of the experiment the visibility was always above 11 km and in our case the variation of the solar radiation was insignificant. The last triple of days the temperature and the diurnal variation was exceptionally higher than the other times.

Date	Max Temp (°C)	Min Temp (°C)	Diurnal variation	Ave Wind speed during night (m/sec)	Wind direction	Visibility (km)
12/07-13/07	28	21	7	3.8	NW & S	11
18/07-19/07	28	22	6	3.7	NW & S	12.5
21/07-22/-7	29	20	9	2.5	S	16.7
25/07-26/07	36	25	11	2.8	S	13.3

Table 24 : Weather conditions of the 4 periods studied.

Results

After collecting the weather data for the days the experiment was carried out the following charts were produced:

- the fluctuation of interior temperature in relation with the exterior temperature
- the temperature difference between interior and exterior temperature (interior-exterior temp) with time.

These charts can be found at Appendix A5 (Figure 81-Figure 96) and concisely are described at the following Table 25

Table of contents for the produced charts

	Material	Shutters control type	Charts
Northern window	uncoated	always open	Temp. to time - Fig. A2.1 ΔTemp to time - Fig. A2.2
	uncoated	always closed	Temp. to time - Fig. A2.3 ΔTemp to time - Fig. A2.4
	uncoated	closed during day (7.00-20.00), open during night (20.00-7.00)	Temp. to time - Fig. A2.5 ΔTemp to time - Fig. A2.6
	aluminium coated	closed during day (7.00-20.00), open during night (20.00-7.00)	Temp. to time - Fig. A2.7 ΔTemp to time - Fig. A2.8
Eastern window	uncoated	always open	Temp. to time - Fig. A2.9 ΔTemp to time - Fig. A2.10
	uncoated	always closed	Temp. to time - Fig. A2.11 ΔTemp to time - Fig. A2.12
	uncoated	closed during day (7.00-20.00), open during night (20.00-7.00)	Temp. to time - Fig. A2.13 ΔTemp to time - Fig. A2.14
	aluminium coated	closed during day (7.00-20.00), open during night (20.00-7.00)	Temp. to time - Fig. A2.15 ΔTemp to time - Fig. A2.16

*Table **25** : Table of contents for the produced charts*

Following, Figure 74 and Figure 75 are the accumulative charts of the northern and eastern window performance so that comparisons could be made. They show the difference between interior and exterior temperature in each case.

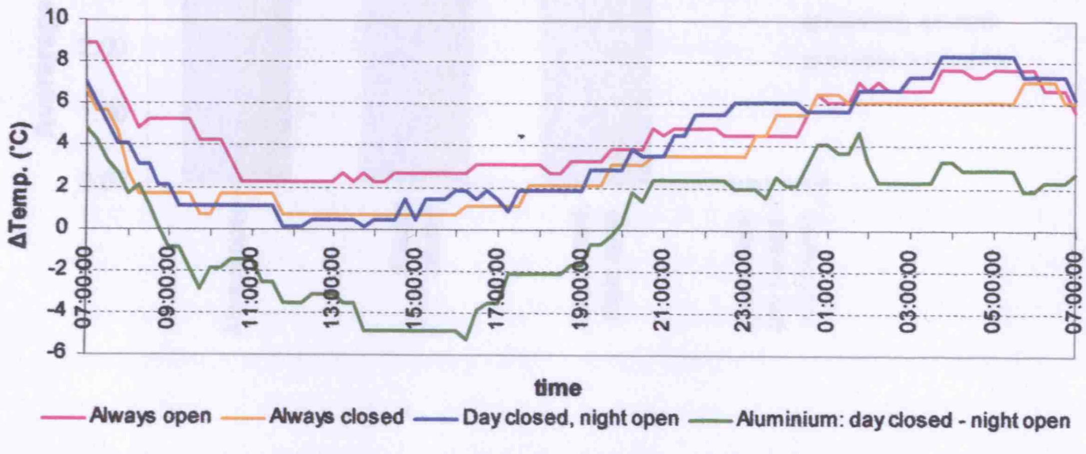


Figure 74 : Accumulative chart: Fluctuation of temperature difference (interior-exterior) for all control types tested (northern window)

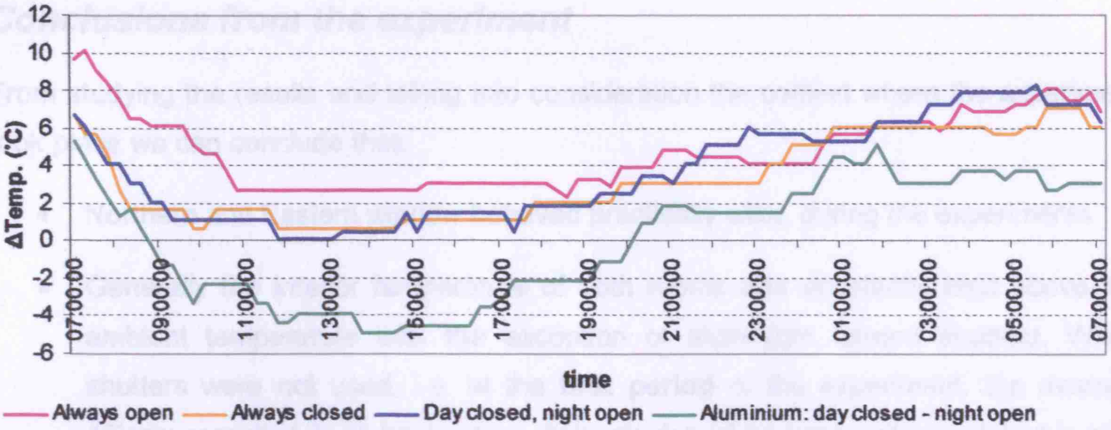


Figure 75 : Accumulative chart: Fluctuation of temperature difference (interior-exterior) for all control types tested (eastern window)

The following Figure 76 gathers the average temperature differences between interior and exterior temperature for each system for the northern and eastern window.

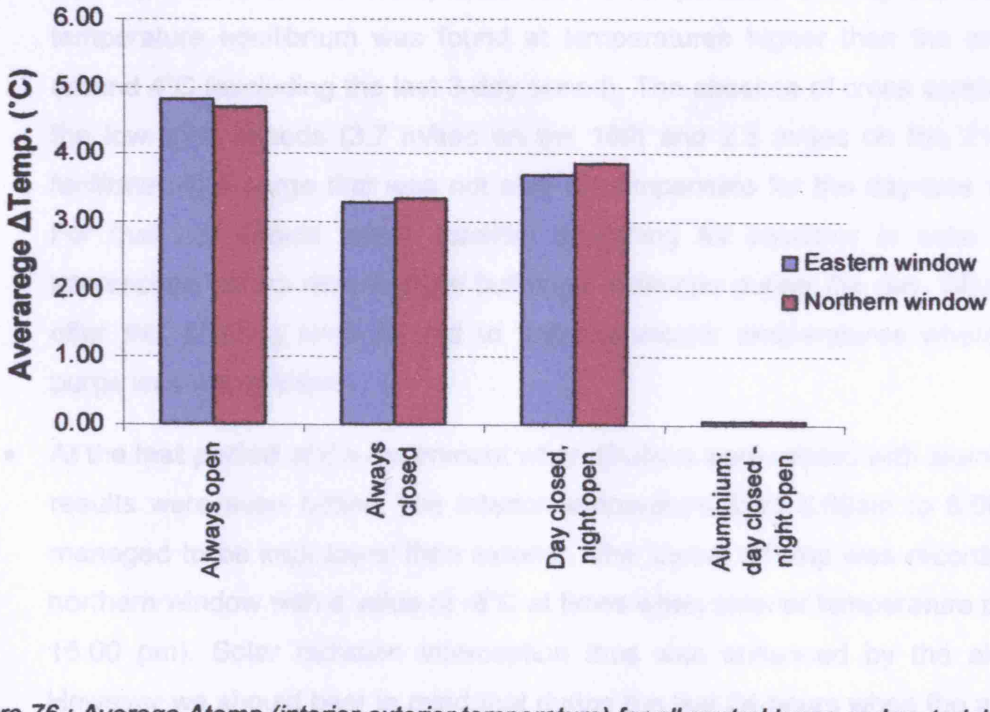


Figure 76 : Average Δtemp (interior-exterior temperature) for all control types and materials tested.

Conclusions from the experiment

From studying the results and taking into consideration the context where the experiment took place we can conclude that:

- Northern and Eastern window behaved practically alike, during the experiments
- Generally the interior temperature of both rooms was constantly kept above the ambient temperature with the exception of aluminium coated shutters. When shutters were not used, i.e. at the **first period** of the experiment, the average ΔTemp recorded its highest values. In particular, when temperatures picked in mid-day the interior temperature exceeded the exterior by around **+3°C**.
- At the **two middle periods**, when shutters were closed during daytime whether or not were applied during night time, interior temperature exceeded the exterior by around **+1°C**, in mid-day when ambient temperatures picked.
- It is worth mentioning that whether or not the shutters were kept open during night the results were practically alike. When the shutters were on during the day the rooms' diurnal temperature variation was between 0.4°C-2°C whereas the ambient was between 6°C-9°C. Thus, there was a temperature stability but the interior temperature equilibrium was found at temperatures higher than the exterior by around 4°C (excluding the last 3-day period). The absence of cross ventilation and the low wind speeds (3.7 m/sec on the 18th and 2.5 m/sec on the 21st) didn't facilitate night purge that was not able to compensate for the day-time overheat. For that, we should better consider searching for solutions in solar radiation interception before reaching the building's envelope during the day. Shutters that offer this shading were proved to improve interior temperatures whereas night purge was not effective.
- At the **last period** of the experiment when shutters were coated with aluminium the results were even better. The interior temperature from 8.00am to 8.00pm was managed to be kept lower than exterior. The lowest ΔTemp was recorded at the northern window with a value of **-5°C** at times when exterior temperature picked (at 16.00 pm). Solar radiation interception thus was enhanced by the aluminium. However we should bear in mind that during the last 24-hours when the aluminium coated shutters was tested the weather was significantly hotter than when the previous tests took place (average ambient temperature was 36°C when previously was 28°C and 29°C). This variance may have magnified the results.

5. General Conclusions

5. General Conclusions

This study initiated with a historical flashback and contemporary architectural trends in regards to windows. After examining the factors that influence the thermal performance of windows, technologies and applications that aim to its improvement were presented. Finally, the basic factors on the choice and design of window shutters were defined. With the completion of the literature review the experimental part of the study took place that had a simulation and a real case experiment.

The simulation examined prototypes of shutters' construction, material and control strategies. There were two main forms of shutters examined: the planar and the louvered shutters. The prototypes were south oriented and were assessed for a Mediterranean climate. The simulation showed that there are potentials in reducing the total load with the appropriate control of shutters. In particular:

Planar shutters:

Six different types of control strategies were examined for four different types of shutters materials: wooden, insulating, translucent and aluminium with insulation. The shutters were compared with a no-shutter window. All systems apart from translucent shutters gave their best performance when shutters were shut at winter nights and summer days when cooling was on and solar radiation on window exceeded 300 W/m².

The simple **wooden shutters** gave a total load reduction of **14%** where **33.5 %** was due to cooling load and **17%** to heating load.

Insulating shutters didn't give significant reduction and translucent shutters gave their best performance with a total transmission of 0.20.

Both **translucent and polished aluminium insulating shutters** gave a similar load reduction of around **18%** but the energy balance was different for each case. The aluminium ones reduced the cooling load by **39%** and the heating load by **22%**.

Louvered shutters:

Louvered shutters were introduced in order to control the lighting load. Three materials were tested; wooden, insulating and polished aluminium with insulation for five control strategies. A fixed angle was proved to result in an increase on total load. The best control strategy was offered by the system that was scheduled to retract during winter days and summer nights, to seal at winter night and to have a fixed angle during summer days.

The simple wooden louvered shutters gave a total load reduction of **18%** with a **38.5%** due to cooling load and **17%** due to heating load. The insulating louvers gave small benefit when compared to the wooden ones.
The best material was proved to be again the polished aluminium with insulation that gave a final total reduction of **23.5%** where **45%** was due to cooling load reduction and **22%** to heating load. The success of the louvered shutter over the planer ones was partially due to the better distribution of solar heat gains throughout the year.

Further to this dissertation a net present cost analysis was carried out. Two constructions were assessed: the simplest wooden planar shutter and the aluminium louvered shutter. The analysis showed that:

- The wooden planar shutter offering **7.9%** energy savings should cost less than **38.5 €/m²** (£ 26.12)
- The polished aluminium & insulating louvered shutter offering **16.7%** energy savings should cost less **81.0 €/m²** (£ 55.0)

However there are many parameters that can influence the above results. Some were examined as the window-to-floor ratio, the orientation and the glazing material of the window. After testing several window-to-floor ratios it was proved that:

- For planar wooden shutters the maximum profitable investment picked when window-to-floor ratio is **0.48** with a cost of **60.80 €/m²**.
- For the aluminium louvered shutters the maximum profitable investment picked when window-to-floor ratio is **0.20** with a cost of **89.90 €/m²**.

When changing window's orientation savings were much bigger for the east and west and much less for the north. In particular:

- For planar wooden shutters oriented east and west energy savings had a max profitable investment of around **63 €/m²**, whereas north resulted in a profitable investment of around **48 €/m²**.
- For aluminium louvers east and west direction had a max profitable investment of around **100 €/m²**, the highest value achieved. For north they were proved costly.

When altering the material of the glazing at south facing windows the study showed that for wooden planar and louvered aluminium shutters profits were significant only for single panes whereas for double panes savings were small.

After the completion of the parameters analysis there was an assessment of thermal comfort due to the application and control of shutters. For free running buildings the aluminium louvered shutters increased by **8.7%** the time that people would give a mean vote between slightly cool and slightly warm thermal feeling.

At the final part of the experimental study a real case experiment was realized at a domestic building at south Greece. Three control strategies were tested and at the end the shutters were covered with aluminium foil. The experiment showed that when shutters were used during the day the interior temperature reduced roughly by 2°C as temperatures picked in the mid-day. When applying aluminium foil on the same shutters the results were more satisfying. In particular when temperatures picked the interior was 5°C lower than the exterior. The combination of ventilation with the opening of the shutters during the night didn't succeed in reducing further the interior temperature that made the application of shutters more effective than night purge for this building.

Appendices

Appendix A1: General Attachments

Appendix A2: Materials and constructions of the simulation model

Appendix A3: Macro used at the simulation

Appendix A4: Tables of the simulation

Appendix A5: Charts of the monitoring

Appendices

Appendix A1: General Attachments

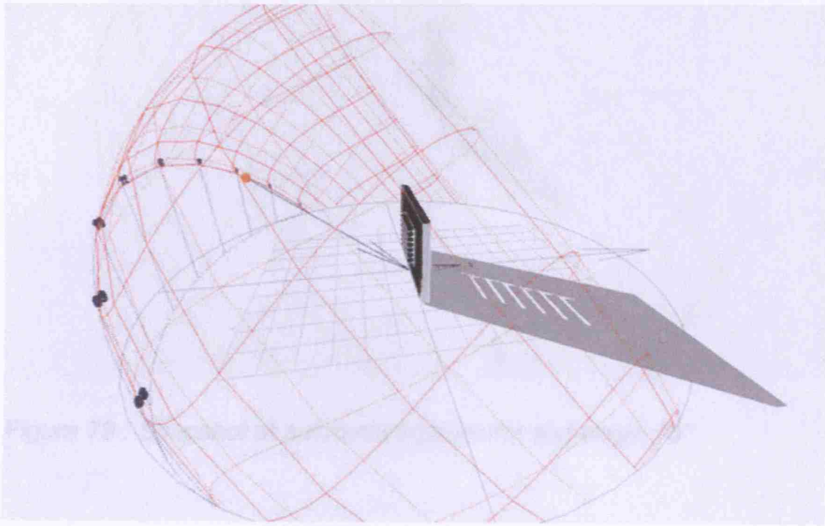


Figure 77 : Snapshot at winter solstice for slat angle 70˚

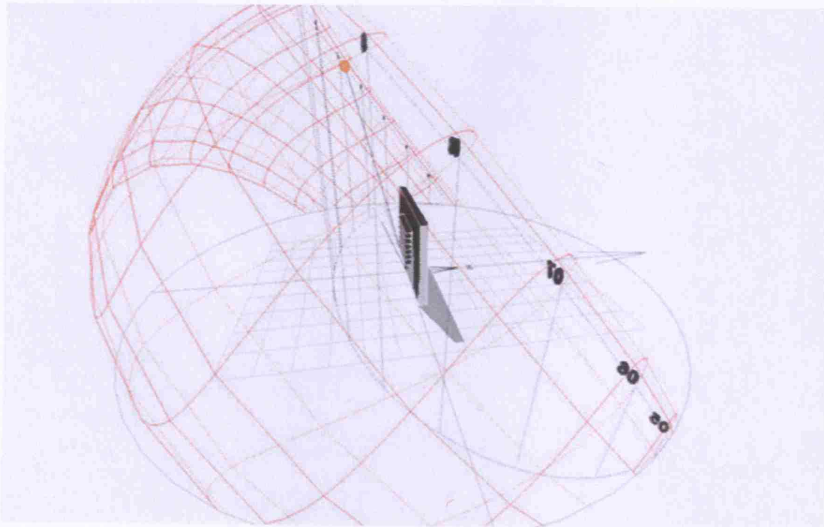


Figure 78 : Snapshot at summer solstice for slat angle 70˚

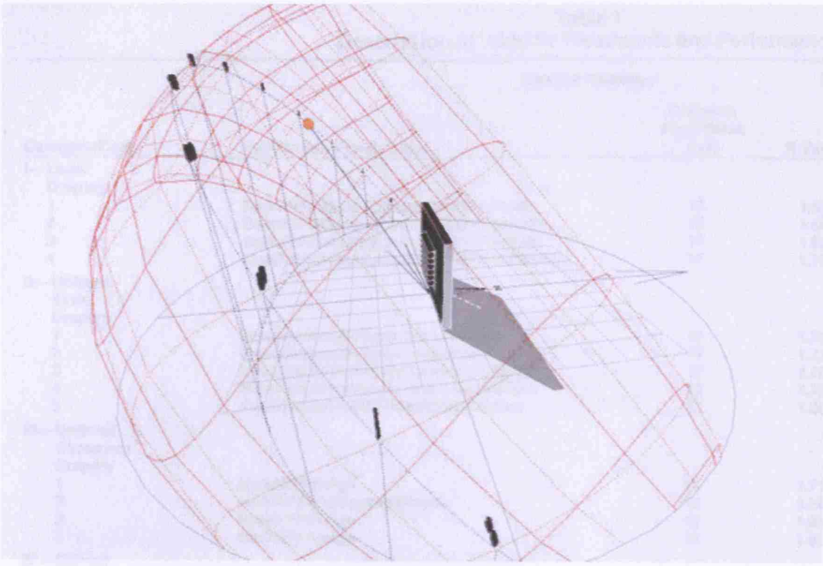


Figure 79 : Snapshot at autumnal equinox for slat angle 70˚

Table 1
Description of Window Treatments and Performance

Category/Code	Window Treatment: Fabrication/Finish/Color	Distance From Glass (cm)	R-Value	Visible Light Transmittance (Flat)	Reflectance	Designator*
I—Lined Drapery						
1	Satin/NFF/Gold (Lining: Plain/Opaque)	12	1.58	.08	.40	IIIM
2	Satin/NFF/Brown (Lining: Plain/Opaque)	12	1.57	.00	.32	IIIM
3	Satin/NFF/White (Lining: Plain/Opaque)	12	1.62	.21	.42	IIIM
4	Mali/NFF/Beige (Lining: Plain/Translucent)	12	1.70	.25	.30	IIM
II—Unlined Satin Drapery						
1	Brocade/Acrylic foam back/Beige	12	1.72	.08	.46	IIIM
2	Brocade/Acrylic foam back/Beige	12	1.72	.05	.46	IIIM
3	Modified Satin/Acrylic foam back/Beige	12	1.70	.17	.46	IIIM
4	Modified Satin/Acrylic foam back/Green	12	1.73	.55	.48	IIIM
5	Modified Satin/NFF/Variegated brown	12	1.65	[illegible]	.26	IIM
III—Unlined Casement Drapery						
1	Mali/NFF/Beige	12	1.71	.45	.24	IM
2	Mali/NFF/Variegated brown	12	1.68	.26	.30	IIM
3	Mali/NFF/Beige	12	1.55	.60	.24	IM
4	Mali/NFF/Beige	12	1.67	.44	.22	IM
IV—Shirred Curtains						
1	Plain (ninon)/NFF/Beige	10	1.74	.66	.20	IM
2	Plain (ninon)/NFF/White	10	1.69	.77	.17	**
3	Leno (marquisette)/NFF/White	10	1.55	.87	.10	**
V—Pleated Curtains						
1	Plain (ninon)/NFF/Beige	12	1.69	.67	.22	IM
VI—Venetian Blinds						
1	2-inch Slats/Steel/NFF/White	13.3	1.46	.08	.31	IIIM
2	1-inch Slats/Aluminum/NFF/White	13.3	1.60	.04	.32	IIIM
VII—Vertical Blinds						
1	3½-inch film/Polyvinylchloride/NFF/White	7.3	1.58	.03	.35	IIIM
2	3½-inch Plain Weave/NFF/White	7.3	1.56	.32	.30	IIM
VIII—Translucent Roller Shade (Without Track)						
1	Open Plain Weave/Vinyl coated fiberglass/Wt	2.5	1.59	.54	.28	IM
2	Plain Weave/Vinyl coated cotton/Beige	2.5	1.80	.19	.38	IIM
3	Perforated film/Aluminum backed/Silver	2.5	1.72	.24	.68	IIIL
1	Open Plain Weave/Vinyl coated fiberglass/Wt	11.4	1.62	.54	.28	IM
2	Plain Weave/Vinyl coated cotton/Beige	11.4	1.68	.19	.38	IIM
3	Perforated film/Aluminum backed/Silver	11.4	1.71	.24	.68	IIIL
IX—Opaque Roller Shade (Without Track)						
1	Plain Weave/Vinyl coated cotton embossed/Bg	2.5	1.73	.02	.36	IIIM
2	Plain Weave/Vinyl coated Millium^R layer/Wt	2.5	2.04	.02	.39	IIIM
3	Plain Weave/Laminated embossed/White	2.5	1.71	.03	.42	IIIM
4	Film/Vinyl coated embossed/White	2.5	1.73	.13	.35	IIIM
1	Plain Weave/Vinyl coated cotton embossed/Bg	11.4	1.79	.02	.36	IIIM
2	Plain Weave/Vinyl coated Millium^R layer/Wt	11.4	1.78	.02	.39	IIIM
3	Plain Weave/Laminated embossed/White	11.4	1.72	.03	.42	IIIM
4	Film/Vinyl coated embossed/White	11.4	1.66	.13	.35	IIIM
X—Rollup Shade						
1	Modified Plain Weave/Vinyl tube yarns/ NFF/Beige	12	1.76	.34	.30	IIM
XI—Drapery Liner						
1	Plain Weave/Acrylic coated/White	12	1.69	.22	.42	IIIM
2	Plain Weave/Acrylic coated/White	12	1.69	.16	.44	IIIM
XII—Wooden Shutter						
1 Louvers Closed	Wood/NFF/Beige	8.9	1.70	.03	.32	IIIM
2 Louvers Open	Wood/NFF/Beige	8.9	1.50	.74	.18	**
XIII—Wooden Shutter Frame with Fabric						
1	Wood/NFF/Beige Ninon/NFF/White (Fabric width 3-times Frame Opening)	8.9	1.75	.62	.21	IM
2	Wood/NFF/Beige Ninon/NFF/White (Fabric width 6-times Frame Opening)	8.9	2.01	.41	.24	IM

Table 26 : Description of window treatments and performance (R-values)
[Source: Horridge P. et al p.46]

Window Treatments Category/Code	Fabrication/Finish/Color	Solar Characteristics		
		Reflectance Percent	Transmittance Percent	Absorptance Percent
I-Lined Drapery				
1	Satin/NFF/Goldenrod Lining: Plain/Opaque/White	66	15	19
2	Satin/NFF/Dark Brown Lining: Plain/Opaque/White	57	02	41
3	Satin/NFF/White Lining: Plain/Opaque/White	68	18	14
4	Mali/NFF/Beige with brown accents Lining: Plain/Translucent/Beige	47	34	19
II-Unlined Satin Drapery				
1	Brocade/Acrylic foam back/Beige	70	08	21
2	Brocade/Acrylic foam back/Beige	67	10	24
3	Modified Satin/Acrylic foam back/Beige	73	17	10
4	Modified Satin/Acrylic foam back/Green	75	09	16
5	Modified Satin/NFF Variegated brown	51	30	19
III-Unlined Casement Drapery				
1	Mali/NFF/Beige	41	54	05
2	Mali/NFF/Variegated brown	54	29	16
3	Mali/NFF/Beige	37	56	07
4	Mali/NFF/Beige	42	36	23
IV-Shirred Curtains				
1	Plain (ninon)/NFF/Beige	27	65	08
2	Plain (ninon)/NFF/White	29	66	05
3	Leno (marquisette)/NFF/White	14	86	00
V-Pleated Curtains				
1	Plain (ninon)/NFF/Beige	37	27	37
VI-Venetian Blinds				
1	2-inch Slats/Steel/NFF/White	55	04	41
2	1-inch Slats/Aluminum/NFF/White	57	02	41
VII-Vertical Blinds				
1	3½-inch Film/Polyvinylchloride/NFF/Wt	70	01	28
2	3½-inch Plain Weave/NFF/White	58	31	11
VIII-Translucent Roller Shade				
1	Open Plain Weave/Vinyl coated fiberglass/White	43	48	09
2	Plain Weave/Vinyl coated cotton/Beige	65	19	16
3	Perforated film/Aluminum backed/Silver	71	21	08
IX-Opague Roller Shade				
1	Plain Weave/Vinyl coated cotton embossed/Beige	66	00	34
2	Plain Weave/Vinyl coated layer/Wt	74	00	26
3	Plain Weave/Laminated embossed/White	75	00	26
4	Film/Vinyl coated embossed/White	67	15	18
X-Rollup Shade				
1	Modified Plain Weave/Vinyl tube yarns/NFF/Beige	53	33	14
XI-Drapery Liner				
1	Plain weave/Acrylic coated/White	66	18	16
2	Plain weave/Acrylic coated/White	70	17	13
XII-Wooden Shutter				
1	Wood/NFF/Beige/Louvers closed	63	00	37
XIII-Wooden Shutter Frame with Fabric				
1	Wood/NFF/Beige; Fabric: Ninon/NFF White/ Width: 3-times Frame Opening/Shirred	35	62	04
2	Wood/NFF/Beige; Fabric: Ninon/NFF White/ Width: 6-times Frame Opening/Shirred	51	32	17

NFF—Functional Finish relevant to Heat Flux.

*Table **27** : Description of window treatment and performance (reflectance, transmission and absorptance)*

[Source: Woodson E. et al,1983, p. 41]

System	Investment		Energy saving per annum			Cost-benefit analysis							
						price of energie							
						6.65 Ecu/GJ (Hfl. 0.60/m3 gas)				13.3 Ecu/GJ (Hfl. 1.20/m3 gas)			
	ECU/m2	(Hfl./m2)	MJ/m2	(m3 gas/m2)	%	PBP y.	ROR %	PWV Ecu	(Hfl.)	PBP y.	ROR %	PWV Ecu	(Hfl.)
Appliances inside													
Single glazing (reference)													
opaque roller blind	9.62	(25)	362	(10.3)	17	4	21	15.95	(41.47)	2	48	31.90	(82.94)
Double glazing (reference)													
opaque roller blind	9.62	(25)	59	(1.6)	6	>10	-	2.48	(6.44)	>10	-	4.95	(12.88)
opaque roller blind, sealed by profiles	28.85	(75)	124	(3.5)	13	>10	-	5.42	(14.09)	>10	-	10.84	(28.18)
opaque roller blind, metallized on one side	37.69	(98)	138	(3.9)	14	>10	-	6.04	(15.70)	>10	-	12.08	(31.40)
opaque roller blind and double reflecting foil	21.15	(55)	250	(7.1)	16	>10	-	10.99	(28.58)	6.5	8.9	21.98	(57.17)
opaque roller blind, sealed by profiles	40.38	(105)	274	(7.8)	29	>10	-	12.08	(31.40)	>10	-	24.15	(62.81)
Double glazing, curtain (reference)													
double reflecting foil	11.54	(30)	176	(5)	20	10	0	7.74	(20.13)	5	15	15.48	(40.26)
Appliances outside													
Double glazing (reference)													
vertical roller screen	113.46	(295)	98	(2.7)	10	>10	-	4.18	(10.87)	>10	-	8.36	(21.74)

PBP = Pay Back Period
ROR = Rate of Return
PWV = Present Worth Value

Table 28:Cost-benefit analysis of several window treatments
[Source: Dubbled M. 1984 p.345]

Appendix A2: Materials and constructions of the simulation model

Cast Concrete slab,	**!- Name**
MediumRough,	!- Roughness
0.15,	!- Thickness {m}
1.33,	!- Conductivity {W/m-K}
2000,	!- Density {kg/m3}
1000,	!- Specific Heat {J/kg-K}
0.9,	!- Absorptance:Thermal
0.7,	!- Absorptance:Solar
0.7;	!- Absorptance:Visible

*Table **29** : Cast Concrete slab*

Extruded Polystyrene,	**!- Name**
MediumSmooth,	!- Roughness
0.05,	!- Thickness {m}
0.035,	!- Conductivity {W/m-K}
40,	!- Density {kg/m3}
1400,	!- Specific Heat {J/kg-K}
0.9,	!- Absorptance:Thermal
0.7,	!- Absorptance:Solar
0.7;	!- Absorptance:Visible

*Table **30** : Extruded Polystyrene*

Brick (protected),	**!- Name**
MediumRough,	!- Roughness
0.09,	!- Thickness {m}
0.7,	!- Conductivity {W/m-K}
1700,	!- Density {kg/m3}
800,	!- Specific Heat {J/kg-K}
0.9,	!- Absorptance:Thermal
0.7,	!- Absorptance:Solar
0.7;	!- Absorptance:Visible

*Table **31** : Brick*

Plaster,	**!- Name**
MediumRough,	!- Roughness
0.02,	!- Thickness {m}
0.21,	!- Conductivity {W/m-K}
700,	!- Density {kg/m3}
1000,	!- Specific Heat {J/kg-K}
0.9,	!- Absorptance:Thermal
0.7,	!- Absorptance:Solar
0.7;	!- Absorptance:Visible

*Table **32** : Plaster*

Ceramic tiles,	**!- Name**
MediumSmooth,	!- Roughness
0.025,	!- Thickness {m}
0.8,	!- Conductivity {W/m-K}
1700,	!- Density {kg/m3}
850,	!- Specific Heat {J/kg-K}
0.9,	!- Absorptance:Thermal
0.7,	!- Absorptance:Solar
0.7;	!- Absorptance:Visible

*Table **33** : Ceramic tiles*

Aggregate,	**!- Name**
VeryRough,	!- Roughness
0.2,	!- Thickness {m}
1.3,	!- Conductivity {W/m-K}
2240,	!- Density {kg/m3}
840,	!- Specific Heat {J/kg-K}
0.9,	!- Absorptance:Thermal
0.7,	!- Absorptance:Solar
0.7;	!- Absorptance:Visible

*Table **34** : Aggregate*

Asphalt,	**!- Name**
Smooth,	!- Roughness
0.003,	!- Thickness {m}
0.5,	!- Conductivity {W/m-K}
1700,	!- Density {kg/m3}
1000,	!- Specific Heat {J/kg-K}
0.9,	!- Absorptance:Thermal
0.7,	!- Absorptance:Solar
0.7;	!- Absorptance:Visible

*Table **35** : Asphalt*

```
MATERIAL:WINDOWGLASS,

  SINGLEPANE,          !- Name
  SpectralAverage,     !- Optical Data Type
  ,                    !- Name of Window Glass Spectral Data Set
  0.006,               !- Thickness {m}
  0.775,               !- Solar Transmittance at Normal Incidence
  0.071,               !- Solar Reflectance at Normal Incidence: Front Side
  0.071,               !- Solar Reflectance at Normal Incidence: Back Side
  0.881,               !- Visible Transmittance at Normal Incidence
  0.080,               !- Visible Reflectance at Normal Incidence: Front Side
  0.080,               !- Visible Reflectance at Normal Incidence: Back Side
  0.0,                 !- IR Transmittance at Normal Incidence
  0.84,                !- IR Hemispherical Emissivity: Front Side
  0.84,                !- IR Hemispherical Emissivity: Back Side
  0.9;                 !- Conductivity {W/m-K}
```

Table **36** *:Singlepane glass*

```
MATERIAL:WINDOWSHADE,

Thermal Shutter_Wooden, !- Name
  0,           !- Solar transmittance
  0.4,         !- Solar Reflectance
  0,           !- Visible transmittance
  0.4,         !- Visible reflectance
  0.9,   !- Thermal hemispherical emissivity
  0,           !- Thermal transmittance
  0.05,        !- Thickness {m}
  0.12,        !- Conductivity {W/m-K}
  0.05,        !- Shade-to-glass distance {m}
  0,           !- Top opening multiplier
  0,           !- Bottom opening multiplier
  0,           !- Left-side opening multiplier
  0,           !- Right-side opening
multiplier
  0;           !- Air flow permeability
```

Table **37** *: Thermal Shutter_Wooden*

```
MATERIAL:WINDOWSHADE,

Thermal Shutter_Insulated, !- Name
  0,           !- Solar transmittance
  0.4,         !- Solar Reflectance
  0,           !- Visible transmittance
  0.4,         !- Visible reflectance
  0.9,   !- Thermal hemispherical emissivity
  0,           !- Thermal transmittance
  0.05,        !- Thickness {m}
  0.035,       !- Conductivity {W/m-K}
  0.05,        !- Shade-to-glass distance {m}
  0,           !- Top opening multiplier
  0,           !- Bottom opening multiplier
  0,           !- Left-side opening multiplier
  0,           !- Right-side opening multiplier
  0;           !- Air flow permeability
```

Table **38** *: Thermal Shutter_Insulated*

Thermal Shutter_Insulated_Thick,	**!-Name**
0,	!- Solar transmittance
0.4,	!- Solar Reflectance
0,	!- Visible transmittance
0.4,	!- Visible reflectance
0.9,	!- Thermal hemispherical emissivity
0,	!- Thermal transmittance
0.10,	!- Thickness {m}
0.035,	!- Conductivity {W/m-K}
0.05,	!- Shade-to-glass distance {m}
0,	!- Top opening multiplier
0,	!- Bottom opening multiplier
0,	!- Left-side opening multiplier
0,	!- Right-side opening multiplier
0;	!- Air flow permeability

Table 39 : Thermal Shutter_Insulated_Thick

Thermal Shutter_Translucent,	**!- Name**
0.4,	!- Solar transmittance
0.4,	!- Solar Reflectance
0.4,	!- Visible transmittance
0.4,	!- Visible reflectance
0.9,	!- Thermal hemispherical emissivity
0,	!- Thermal transmittance
0.05,	!- Thickness {m}
0.035,	!- Conductivity {W/m-K}
0.05,	!- Shade-to-glass distance {m}
0,	!- Top opening multiplier
0,	!- Bottom opening multiplier
0,	!- Left-side opening multiplier
0,	!- Right-side opening multiplier
0;	!- Air flow permeability

Table 40 : Thermal Shutter_Translucent

Thermal Shutter_Aluminum (roughly polished) coated & Insulating,	**!- Name**
0,	!- Solar transmittance
0.5,	!- Solar Reflectance
0,	!- Visible transmittance
0.5,	!- Visible reflectance
0.22,	!- Thermal hemispherical emissivity
0,	!- Thermal transmittance
0.05,	!- Thickness {m}
0.035,	!- Conductivity {W/m-K}
0.05,	!- Shade-to-glass distance {m}
0,	!- Top opening multiplier
0,	!- Bottom opening multiplier
0,	!- Left-side opening multiplier
0,	!- Right-side opening multiplier
0;	!- Air flow permeability

Table 41 : Thermal Shutter_Aluminum (roughly polished)

Thermal Shutter_Aluminum (highly polished) coated & Insulating,	**!- Name**
0,	!- Solar transmittance
0.9,	!- Solar Reflectance
0,	!- Visible transmittance
0.9,	!- Visible reflectance
0.1,	!- Thermal hemispherical emissivity
0,	!- Thermal transmittance
0.05,	!- Thickness {m}
0.035,	!- Conductivity {W/m-K}
0.05,	!- Shade-to-glass distance {m}
0,	!- Top opening multiplier
0,	!- Bottom opening multiplier
0,	!- Left-side opening multiplier
0,	!- Right-side opening multiplier
0;	!- Air flow permeability

Table 42 : Thermal Shutter_Aluminum (highly polished)

```
Blind_wooden,      !- Name
  Horizontal,       !- Slat orientation
  0.2,             !- Slat width {m}
  0.2,             !- Slat separation {m}
  0.05,            !- Slat thickness {m}
  60,              !- Slat angle {deg}
  0.12,            !- Slat conductivity {W/m-K}
  0,               !- Slat beam solar transmittance
  0.4,             !- Slat beam solar reflectance, front side
  0.4,             !- Slat beam solar reflectance, back side
  0,               !- Slat diffuse solar transmittance
  0.4,             !- Slat diffuse solar reflectance, front side
  0.4,             !- Slat diffuse solar reflectance, back side
  0,               !- Slat beam visible transmittance
  0.4,             !- Slat beam visible reflectance, front side
  0.4,             !- Slat beam visible reflectance, back side
  0,               !- Slat diffuse visible transmittance
  0.4,             !- Slat diffuse visible reflectance, front side
  0.4,             !- Slat diffuse visible reflectance, back side
  0,               !- Slat IR (thermal) hemispherical transmittance
  0.9,             !- Slat IR (thermal) hemispherical emissivity, front side
  0.9,             !- Slat IR (thermal) hemispherical emissivity, back side
  0.1,             !- Blind-to-glass distance {m}
  0,               !- Blind top opening multiplier
  0,               !- Blind bottom opening multiplier
  0,               !- Blind left-side opening multiplier
  0,               !- Blind right-side opening multiplier
  0,               !- Minimum Slat Angle {deg}
  180;             !- Maximum Slat Angle {deg}
```

Table 43 : Louvered shutter_Wooden

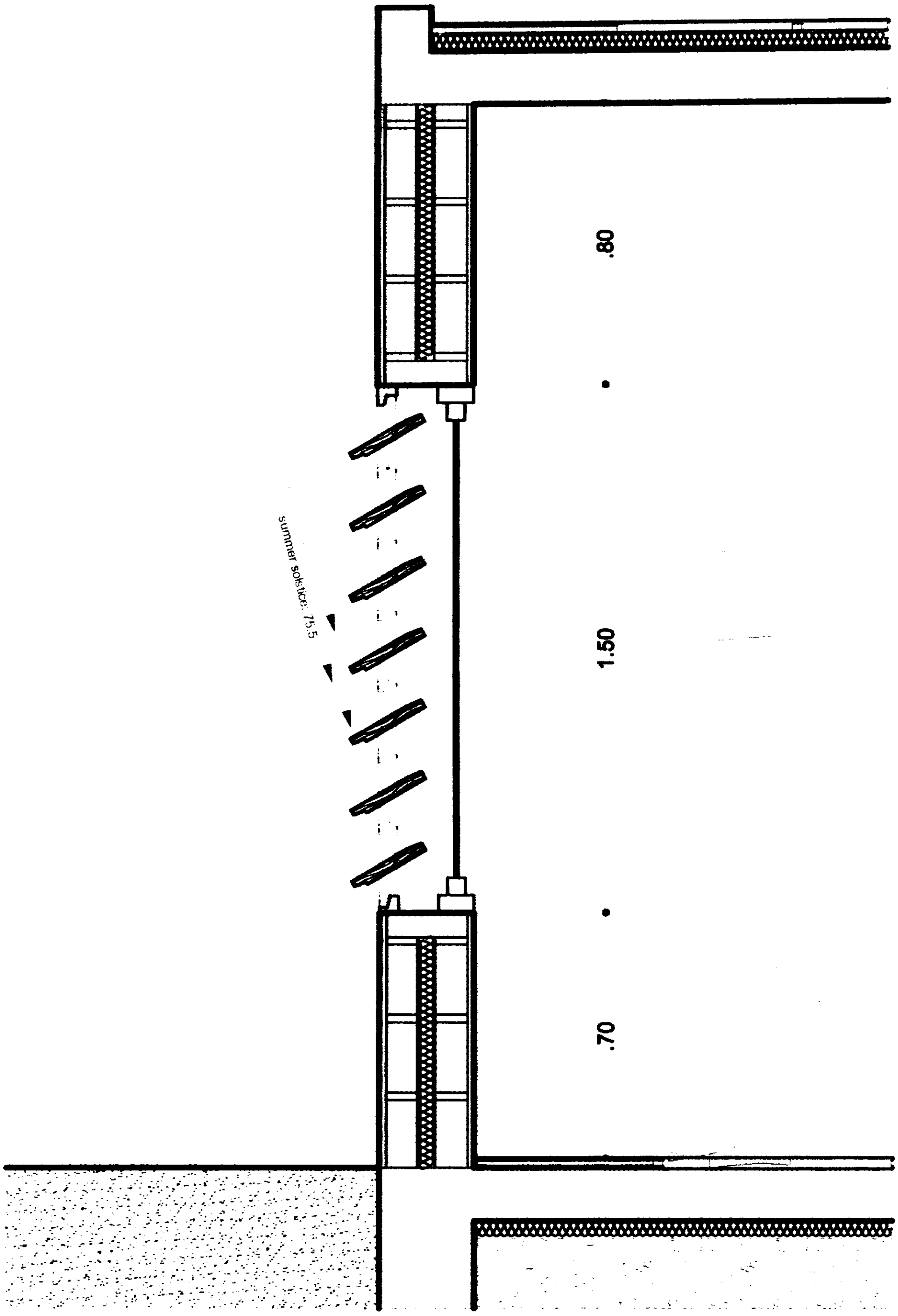
```
Blind_Insulating,  !- Name
  Horizontal,       !- Slat orientation
  0.2,             !- Slat width {m}
  0.2,             !- Slat separation {m}
  0.05,            !- Slat thickness {m}
  60,              !- Slat angle {deg}
  0.035,           !- Slat conductivity {W/m-K}
  0,               !- Slat beam solar transmittance
  0.4,             !- Slat beam solar reflectance, front side
  0.4,             !- Slat beam solar reflectance, back side
  0,               !- Slat diffuse solar transmittance
  0.4,             !- Slat diffuse solar reflectance, front side
  0.4,             !- Slat diffuse solar reflectance, back side
  0,               !- Slat beam visible transmittance
  0.4,             !- Slat beam visible reflectance, front side
  0.4,             !- Slat beam visible reflectance, back side
  0,               !- Slat diffuse visible transmittance
  0.4,             !- Slat diffuse visible reflectance, front side
  0.4,             !- Slat diffuse visible reflectance, back side
  0,               !- Slat IR (thermal) hemispherical transmittance
  0.9,             !- Slat IR (thermal) hemispherical emissivity, front side
```

```
0.9,        !- Slat IR (thermal) hemispherical emissivity, back side
0.1,        !- Blind-to-glass distance {m}
0,          !- Blind top opening multiplier
0,          !- Blind bottom opening multiplier
0,          !- Blind left-side opening multiplier
0,          !- Blind right-side opening multiplier
0,          !- Minimum Slat Angle {deg}
180;        !- Maximum Slat Angle {deg}
```

Table 44 : Louvered shutter_Insulating

```
Blind_Polished Alum Insulating, !- Name
Horizontal,   !- Slat orientation
0.2,          !- Slat width {m}
0.2,          !- Slat separation {m}
0.05,         !- Slat thickness {m}
60,           !- Slat angle {deg}
0.035,        !- Slat conductivity {W/m-K}
0,            !- Slat beam solar transmittance
0.9,          !- Slat beam solar reflectance, front side
0.9,          !- Slat beam solar reflectance, back side
0,            !- Slat diffuse solar transmittance
0.9,          !- Slat diffuse solar reflectance, front side
0.9,          !- Slat diffuse solar reflectance, back side
0,            !- Slat beam visible transmittance
0.9,          !- Slat beam visible reflectance, front side
0.9,          !- Slat beam visible reflectance, back side
0,            !- Slat diffuse visible transmittance
0.9,          !- Slat diffuse visible reflectance, front side
0.9,          !- Slat diffuse visible reflectance, back side
0,            !- Slat IR (thermal) hemispherical transmittance
0.1,          !- Slat IR (thermal) hemispherical emissivity, front side
0.1,          !- Slat IR (thermal) hemispherical emissivity, back side
0.1,          !- Blind-to-glass distance {m}
0,            !- Blind top opening multiplier
0,            !- Blind bottom opening multiplier
0,            !- Blind left-side opening multiplier
0,            !- Blind right-side opening multiplier
0,            !- Minimum Slat Angle {deg}
180;          !- Maximum Slat Angle {deg}
```

Table 45 : Louvered shutter_Polished aluminium



section scale 1:20

Figure 80: Section of the model

Appendix A3: Macro used at the simulation

The initial macro command was produced by Dr Ian Ridley. In particular, the following Macro is used for Control Type D.

```
Dim sDay As String
Dim sMonth As String
Dim r As Integer
Dim c(100) As Integer
Dim Unit(100) As Integer
Dim Filename(100) As String
Dim Vents(100) As String
Dim i As Integer
Dim Buff As String
Dim h As Single
Dim d As Integer
Dim sDate As String
Dim sTime As String
Dim sDateTime As String
Dim Arr
Dim sLastDate As String
Dim delim As String
Dim DayCount As Long
Dim DaySchedules(1 To 7, 100) As String
Dim WeekSchedules(1 To 52, 100) As String
Dim StartWeek(1 To 52) As String
Dim EndWeek(1 To 52) As String
Dim WeekCount As Long
Dim wd As Long

Sub Main()

  On Error GoTo Error:

 Vents(1) = "SlatAngle"

 Vents(25) = "SlatAngleOutput"

  Filename(9) = "E:\UCL\dissertation\Energy Plus\Window Blind_Wooden\" & Vents(25) & ".txt"
  Unit(9) = FreeFile
  Open Filename(9) For Output As Unit(9)



  c(1) = 2   ' relevant column




  For i = 1 To 1


  DayCount = 0
  WeekCount = 0

  'For r = 2 To 169
  For r = 2 To 8761

    sDateTime = Cells(r, 1)
```

```
Arr = Split(sDateTime, " ")
sDate = Arr(1)
sTime = Mid(Arr(3), 1, Len(Arr(3)) - 3)

Arr = Split(sDate, "/")

sMonth = Arr(0)
sDay = Arr(1)

' if its a new day Write new dayschedule:list
If sLastDate <> sDate Then

   DayCount = DayCount + 1

   If DayCount = 8 Then

      NewWeek False, i

   End If

   'For i = 1 To 2

      Print #Unit(9), "DAYSCHEDULE:LIST,"
      Print #Unit(9), Vents(i) & "_" & sDate & ","
      Print #Unit(9), "Angle,"
      Print #Unit(9), "No,60,"

      DaySchedules(DayCount, i) = Vents(i) & "_" & sDate

   'Next

End If

sLastDate = sDate

If Val(sTime) = 24 Then

   delim = ";"

Else

   delim = ","

End If

'If Abs(Cells(r, c)) > 10 Then

   'Print #Unit(1), "0.0" & delim
   'Print #Unit(2), "1.0" & delim

' Else

   'Print #Unit(1), "1.0" & delim
   'Print #Unit(2), "0.0" & delim

'End If

x = Worksheets("Simulated").Cells(r, 5).Value
y = Worksheets("Simulated").Cells(r, 2).Value
z = Worksheets("Simulated").Cells(r, 17).Value

 If y = 1 Or (x > 400 And z > 0) Then

 Print #Unit(9), 0 & delim

 Else: Print #Unit(9), 90 & delim
```

```
        End If



        '___________________________

    Next

    ' block copied from above
    DayCount = DayCount + 1

    If DayCount = 8 Then

        ' new week - write weekschedule for previous week
        'NewWeek True
        NewWeek True, i
    End If

    ' generate schedules
    Schedules i

    'Close #Unit(1)
    'Close #Unit(2)
    Next i
    Close #Unit(9)

    MsgBox "Data processed OK"

    Exit Sub

Error:

    MsgBox "Error processing data"
    Exit Sub

End Sub


Sub Schedules(i)

    Dim d As Long

    ' new week - write weekschedule for previous week
    DayCount = 1

    'For i = 1 To 2

        Print #Unit(9), "SCHEDULE,"
        Print #Unit(9), Vents(i) & ","
        Print #Unit(9), "Angle" & ","

        d = DateSerial(2003, 1, 1)

        ' 7 days in week
        For wd = 1 To WeekCount

            If wd = WeekCount Then

                delim = ";"

            Else

                delim = ","

            End If

            Print #Unit(9), WeekSchedules(wd, i) & "," & StartWeek(wd) & "," & EndWeek(wd) & delim
```

```
      Next

   'Next i

End Sub

Sub NewWeek(Last As Boolean, i)

   ' last passed in as true for last call - in this case the last weekschedule should run through to end
of year
   Dim dat As Date

   ' new week - write weekschedule for previous week
   DayCount = 1

   WeekCount = WeekCount + 1

   'If Last Then

   If WeekCount = 52 Then

      EndWeek(WeekCount) = "12, 31"

   Else

      EndWeek(WeekCount) = sMonth & "," & (sDay - 1)

   End If

   ' start of week
   dat = DateSerial(2003, sMonth, sDay) - 7

   StartWeek(WeekCount) = Month(dat) & "," & Day(dat)

  ' For i = 1 To 2

      ' new weekschedule - store name
      WeekSchedules(WeekCount, i) = Vents(i) & "_" & WeekCount
      Print #Unit(9), "WEEKSCHEDULE,"
      Print #Unit(9), WeekSchedules(WeekCount, i) & ","

      ' 7 days in week
      For wd = 1 To 7

         Print #Unit(9), DaySchedules(wd, i) & ","

      Next

      ' holidays etc.
      For wd = 1 To 4

         Print #Unit(9), "Off,"

      Next

      Print #Unit(9), "Off;"

  'Next

End Sub
```

Appendix A4: Tables of the simulation

Materials and Control types	Setpoint	Light. Load - kWh	Heat. Load - kWh	Cool. Load - kWh	Total Load - kWh
Control Type_C:off Night /on Day if cooling on and HighSolar Radiation on Window					
Control Type_C	400W/m²	380.06	549.94	473.35	1403.35
Control Type_C	350W/m²	405.63	549.94	431.39	1386.95
Control Type_C	300W/m²	422.76	549.94	410.87	1383.57
Control Type_C	250W/m²	437.70	549.94	399.24	1386.88
Control Type_C	200W/m²	451.56	549.94	393.34	1394.84
Control Type_C	100W/m²	485.32	549.94	392.47	1427.73
Control Type_D:on Night if low out C/off day					
Control Type_D	14°	331.09	437.91	618.60	1387.59
Control Type_D	15°	331.09	434.52	618.86	1384.47
Control Type_D	16°	331.09	432.93	619.18	1383.20
Control Type_D	17°	331.09	432.23	619.39	1382.71
Control Type_D	18°	331.09	431.71	620.26	1383.07
Control Type_D	19°	331.09	431.56	622.75	1385.39

Table 46 : Annual loads of planar wooden shutters for various setpoint values of control type C & D.

Materials and Control types	Setpoint	Light. Load - kWh	Heat. Load - kWh	Cool. Load - kWh	Total Load - kWh
Wooden Louvers_Control Type 0 - Fixed slat angles					
No shutter (base case)		331.09	549.94	618.59	1499.62
Control Type_0	0°(sealed)	955.57	552.88	566.12	2074.56
Control Type_0	15°	792.31	684.58	486.10	1962.99
Control Type_0	30°	670.16	874.39	385.80	1930.36
Control Type_0	45°	598.67	889.97	379.32	1867.96
Control Type_0	60°	542.05	875.55	382.88	1800.48
Control Type_0	75°	499.30	830.22	388.34	1717.86

Control Type_0	90°	473.35	761.68	393.84	1628.87
Control Type_0	105°	461.51	687.62	397.75	1546.88
Control Type_0	120°	466.05	632.86	406.43	1505.34
Control Type_0	135°	488.23	660.08	427.39	1575.71
best choice	120°	466.05	632.86	406.43	1505.34
% variation from base case		-40.76	-15.08	34.30	-0.38

*Table **47** : Annual loads of wooden louvered shutters for Control Type 0.*

Materials and Control types	Setpoint	Light. Load - kWh	Heat. Load - kWh	Cool. Load - kWh	Total Load - kWh
Wooden Louvers_Control Type A: Scheduled to retract winter days and summer nights. Else slat angle is set.					
No shutter (base case)		331.09	549.94	618.59	1499.62
Control Type_A	0°	623.52	456.40	517.30	1597.22
Control Type_A	15°	550.58	476.88	451.70	1479.17
Control Type_A	30°	485.92	509.77	365.98	1361.67
Control Type_A	45°	452.18	514.92	362.11	1329.20
Control Type_A	60°	427.82	516.61	366.64	1311.07
Control Type_A	75°	409.10	517.48	372.42	1299.00
Control Type_A	90°	398.40	517.72	377.81	1293.93
Control Type_A	105°	394.33	517.48	381.27	1293.08
Control Type_A	120°	398.56	516.61	389.04	1304.20
Control Type_A	135°	398.56	516.61	389.04	1304.20
best choice	90°&105°	398.40	517.72	377.81	1293.93
% variation from base case		-20.33	5.86	38.92	13.72

*Table **48** : Annual loads for several slat angles for Control Type A of wooden louvered shutters*

Materials and Control types	Setpoint	Light. Load - kWh	Heat. Load - kWh	Cool. Load - kWh	Total Load - kWh
Wooden Louvers_Control Type B: Scheduled to retract winter days and summer nights. If it is winter night slats close. Else slat angle is set.					
No shutter (base case)		331.09	549.94	618.59	1499.62
Control Type_B	60º	427.82	456.40	366.64	1250.86
Control Type_B	75º	409.25	456.40	372.04	1237.68
Control Type_B	90º	398.40	456.40	377.81	1232.61
Control Type_B	105º	394.41	456.40	380.88	1231.68
Control Type_B	120º	399.02	456.40	389.23	1244.65
best choice	105º	394.41	456.40	380.88	1231.68
% variation from base case		-19.12	17.01	38.43	17.87

*Table **49** : Annual loads of wooden louvered thermal shutter for several setpoint values of Control Type B*

Materials and Control types	Setpoint	Light. Load - kWh	Heat. Load - kWh	Cool. Load - kWh	Total Load - kWh
Wooden Louvers_Control Type_C: Scheduled to retract at winter days and summer nights. If it is winter night and if (cooling is on and solar radiation on window exceeds a setpoint) slats close. Else slat angle 90.					
No shutter (base case)		331.09	549.94	618.59	1499.62
Control Type C	300 W/m²	413.53	456.40	395.57	1265.50
Control Type_C	400 W/m²	403.64	456.40	384.47	1244.51
Control Type_C	450 W/m²	400.10	456.40	379.90	1236.39
best choice	450 W/m²	400.10	456.40	379.90	1236.39
% variation from base case		-20.84	17.01	38.59	17.55

*Table **50** : Annual loads of wooden louvered thermal shutter for several setpoint values of Control Type C*

Materials and Control types	Setpoint	Light. Load - kWh	Heat. Load - kWh	Cool. Load - kWh	Total Load - kWh
Wooden Louvers_Control Type_D_400: Scheduled to retracted at winter days and summer nights. If it is winter night and if cooling power is high slats close. Else slat angle is 90°.					
No shutter (base case)		331.09	549.94	618.59	1499.62
Control Type_D	400 W	410.42	456.40	386.74	1253.56
Control Type_D	500 W	400.77	456.40	379.21	1236.37
Control Type_D	600 W	400.01	456.40	378.81	1235.22
best choice	600 W	400.01	456.40	378.81	1235.22
% variation from base case		-20.81	17.01	38.76	17.63

Table 51 : Annual loads of wooden louvered thermal shutter for several setpoint values of Control Type D

Materials and Control types	Setpoint	Light. Load - kWh	Heat. Load - kWh	Cool. Load - kWh	Total Load - kWh
Polished Aluminium Coated & Insul. Louvers_Control Type 0 - Fixed slat angles					
No shutter (base case)		331.09	549.94	618.59	1499.62
Control Type_0	0°(sealed)	955.57	667.70	429.82	2053.10
Control Type_0	15°	599.02	822.39	351.38	1772.79
Control Type_0	30°	499.51	905.59	337.56	1742.66
Control Type_0	45°	447.12	880.23	353.07	1680.43
Control Type_0	60°	421.09	836.47	377.10	1634.66
Control Type_0	75°	406.91	776.94	399.69	1583.54
Control Type_0	90°	399.30	708.12	412.19	1519.61
Control Type_0	105°	398.85	643.85	416.23	1458.94
Control Type_0	120°	403.51	601.85	422.80	1428.15
Control Type_0	135°	417.50	636.76	437.99	1492.25
best choice	120°	403.51	601.85	422.80	1428.15
% variation from base case		-21.87	-9.44	31.65	4.77

Table 52 : Annual loads of polished Aluminium coated louvered shutter for several setpoint values of Control Type 0

Materials and Control types	Setpoint	Light. Load - kWh	Heat. Load - kWh	Cool. Load - kWh	Total Load - kWh
Polished Aluminium Coated & Insul. Louvers_Control Type A: Scheduled to retract winter days and summer nights. Else slat angle is set.					
No shutter (base case)		331.09	549.94	618.59	1499.62
Control Type_A	0°	623.52	430.26	374.67	1428.45
Control Type_A	15°	456.63	467.07	319.17	1242.88
Control Type_A	30°	409.82	505.52	318.28	1233.61
Control Type_A	45°	381.33	513.22	336.68	1231.23
Control Type_A	60°	368.78	516.55	362.08	1247.41
Control Type_A	75°	362.49	518.24	385.32	1266.05
Control Type_A	90°	359.37	518.69	397.80	1275.86
Control Type_A	105°	359.70	518.24	401.30	1279.24
Control Type_A	120°	362.64	516.54	406.22	1285.40
best choice	45°	381.33	513.22	336.68	1231.23
% variation from base case		-15.17	6.68	45.57	17.90

*Table **53** : Annual loads of polished Aluminium coated louvered shutter for several setpoint values of Control Type A*

Materials and Control types	Setpoint	Light. Load - kWh	Heat. Load - kWh	Cool. Load - kWh	Total Load - kWh
Polished Aluminium Coated & Insul. Louvers_Control Type B: Scheduled to retract winter days and summer nights. If it is winter night slats close. Else slat angle is set.					
No shutter (base case)		331.09	549.94	618.59	1499.62
Control Type_B	30°	409.82	430.26	318.28	1158.35
Control Type_B	45°	381.48	430.26	336.49	1148.23
Control Type_B	75°	362.53	430.26	384.35	1177.13
Control Type_B	60°	368.78	430.26	362.08	1161.12
Control Type_B	90°	359.37	430.26	397.80	1187.44
best choice	45°	381.48	430.26	336.49	1148.23
% variation from base case		-15.22	21.76	45.60	23.43

*Table **54** : Annual loads of polished Aluminium coated louvered shutter for several setpoint values of Control Type B*

Materials and Control types	Setpoint	Light. Load - kWh	Heat. Load - kWh	Cool. Load - kWh	Total Load - kWh
Polished Aluminium Coated & Insul. Louvers_Control Type_C: Scheduled to retracted at winter days and summer nights. If it is winter night and if (cooling is on and solar radiation on window exceeds a setpoint) slats close. Else slat angle is 45˚.					
No shutter (base case)		331.09	549.94	618.59	1499.62
Control Type_C	300 W/m²	396.73	430.26	336.04	1163.03
Control Type_C	400 W/m²	386.72	430.26	336.38	1153.36
Control Type_C	450 W/m²	383.18	430.26	336.50	1149.94
best choice	450 W/m²	383.18	430.26	336.50	1149.94
% variation from base case		-15.73	21.76	45.60	23.32

Table 55 : Annual loads of polished Aluminium coated louvered shutter for several setpoint values of Control Type C

Materials and Control types	Setpoint	Light. Load - kWh	Heat. Load - kWh	Cool. Load - kWh	Total Load - kWh
Polished Aluminium Coated & Insul. Louvers_D_400: Scheduled to retracted at winter days and summer nights. If it is winter night and if cooling power is high slats close. Else slat angle is 45˚.					
No shutter (base case)		331.09	549.94	618.59	1499.62
Control Type_D	400 W	391.29	430.26	337.20	1158.75
Control Type_D	450 W	385.86	430.26	336.49	1152.61
Control Type_D	500 W	382.85	430.26	336.54	1149.65
best choice	500 W	382.85	430.26	336.54	1149.65
% variation from base case		-15.63	21.76	45.60	23.34

*Table **56** : Annual loads of polished Aluminium coated louvered shutter for several setpoint values of Control Type D*

Materials and Control types	Window to Floor Ratio	Light. Load kWh	Heat. Load kWh	Cool. Load kWh	Total Load kWh	Consumption kWh	Savings kWh	Savings %	Savings per shutter area €/m²	Maximum Profitable Investment €/m²
Wooden Planar Shutter__Control Type F / Window to Floor Ratio Parameter										
No shutter	0.12	331.09	549.94	618.59	1499.62	1149.98				
>>	0.16	323.51	489.51	747.49	1560.50	1138.01				
>>	0.20	318.86	444.83	879.00	1642.68	1145.86				
>>	0.24	315.84	412.54	1010.59	1738.96	1167.76				
>>	0.28	313.58	390.04	1140.82	1844.43	1199.62				
>>	0.32	308.83	376.34	1266.24	1951.41	1235.71				
>>	0.36	306.62	367.25	1390.41	2064.27	1278.39				
>>	0.40	306.30	361.59	1512.57	2180.46	1325.53				
>>	0.44	305.79	359.55	1631.26	2296.60	1374.58				
>>	0.48	305.06	360.56	1746.11	2411.73	1424.80				
>>	0.52	304.35	364.17	1855.96	2524.48	1475.46				
>>	0.56	303.74	369.79	1962.17	2635.70	1526.65				
>>	0.60	303.26	375.42	2042.07	2720.75	1566.53				
Wooden Shutter	0.12	422.80	456.94	411.45	1291.19	1058.63	91.35	7.94	3.11	38.56
>>	0.16	418.49	377.33	436.73	1232.55	985.70	152.31	13.38	3.89	48.22
>>	0.20	416.92	317.41	461.21	1195.53	934.85	211.01	18.41	4.31	53.44
>>	0.24	416.67	273.37	485.87	1175.91	901.29	266.47	22.82	4.54	56.24
>>	0.28	416.41	240.11	509.84	1166.36	878.19	321.43	26.79	4.69	58.14
>>	0.32	413.08	215.90	532.72	1161.70	860.60	375.11	30.36	4.79	59.37
>>	0.36	412.38	197.24	555.38	1164.99	851.09	427.30	33.43	4.85	60.12
>>	0.40	413.25	182.56	578.43	1174.24	847.30	478.23	36.08	4.89	60.56
>>	0.44	413.78	171.84	600.24	1185.87	846.60	527.99	38.41	4.91	60.78
>>	0.48	414.09	164.54	620.67	1199.29	848.48	576.32	40.45	4.91	60.81
>>	0.52	413.92	159.88	641.51	1215.31	852.72	622.74	42.21	4.90	60.66
>>	0.56	413.85	156.97	661.36	1232.18	858.37	668.28	43.77	4.88	60.44
>>	0.60	413.72	155.83	676.66	1246.20	863.75	702.79	44.86	4.79	59.33

Table 57 : Window to floor area parameter: Loads, savings and profits of the wooden planar shutter (with control type F).

Materials and Control types	Window to Floor Ratio	Light. Load kWh	Heat. Load kWh	Cool. Load kWh	Total Load kWh	Consumption kWh	Savings kWh	Savings %	Savings per shutter area €/m²	Maximum Profitable Investment €/m²
Pol. Aluminium Coated & Insul. Louvers - Control Type_B / Window to Floor Ratio Parameter										
Alum. Louvers	0.12	381.48	430.26	336.49	1148.23	958.04	191.94	16.69	6.54	81.02
>>	0.16	362.64	346.05	346.16	1054.85	859.19	278.82	24.50	7.12	88.26
>>	0.20	351.11	283.76	358.72	993.59	790.84	355.02	30.98	7.26	89.91
>>	0.24	343.24	237.47	372.36	953.07	742.61	425.15	36.41	7.24	89.73
>>	0.28	337.46	202.36	386.44	926.25	707.83	491.79	41.00	7.18	88.96
>>	0.32	328.07	177.04	399.32	904.43	678.73	556.98	45.07	7.12	88.16
>>	0.36	323.30	157.72	413.27	894.29	660.70	617.69	48.32	7.01	86.91
>>	0.40	321.95	143.00	428.01	892.95	651.03	674.49	50.88	6.89	85.41
>>	0.44	320.36	132.18	442.43	894.98	644.91	729.68	53.08	6.78	84.00
>>	0.48	318.51	124.33	456.55	899.39	641.34	783.46	54.99	6.67	82.67
>>	0.52	316.79	118.83	469.90	905.52	639.93	835.53	56.63	6.57	81.38
>>	0.56	315.30	115.21	482.98	913.49	640.50	886.15	58.05	6.47	80.15
>>	0.60	314.19	113.35	492.82	920.35	641.80	924.73	59.03	6.30	78.06

*Table **58** : Window to floor area parameter: Loads, savings and profits of the aluminium louvered shutter (with control type B).*

Materials and Control types	Orientation	Light. Load kWh	Heat. Load kWh	Cool. Load kWh	Total Load kWh	Consumption kWh	Savings kWh	Savings %	Savings per shutter area €/m²	Maximum Profitable Investment €/m²
Wooden Planar Shutter__Control Type F / Orientation Parameter										
No shutter	south	331.09	549.94	618.59	1499.62	1149.98				
>>	west	332.76	831.05	723.63	1887.43	1478.42				
>>	north	338.77	990.45	394.07	1723.29	1500.55				
>>	east	335.58	821.41	736.66	1893.65	1477.28				
Wooden Shut.ter Contr F	south	422.80	456.94	411.45	1291.19	1058.63	91.35	7.94	3.11	38.56
>>	west	418.77	724.29	428.63	1571.69	1329.42	149.01	10.08	5.08	62.89
>>	north	338.77	876.65	394.43	1609.85	1386.91	113.65	7.57	3.87	47.97
>>	east	417.70	716.31	444.56	1578.57	1327.30	149.98	10.15	5.11	63.30

*Table **59** : Orientation parameter: Loads, savings and profits of the wooden planar shutter (with control type F).*

Materials and Control types	Orientation	Light. Load kWh	Heat. Load kWh	Cool. Load kWh	Total Load kWh	Consumption kWh	Savings kWh	Savings %	Savings per shutter area €/m²	Maximum Profitable Investment €/m²
Pol. Aluminium Coated & Insul. Louvers - Control Type_B/ Orientation Parameter										
No shutter	south	331.09	549.94	618.59	1499.62	1149.98				
>>	west	332.76	831.05	723.63	1887.43	1478.42				
>>	north	338.77	990.45	394.07	1723.29	1500.55				
>>	east	335.58	821.41	736.66	1893.65	1477.28				
Alum. Louvers	south	381.48	430.26	336.49	1148.23	958.04	191.94	16.69	6.54	81.02
>>	west	385.7	692.29	360.36	1438.3	1234.66	243.76	16.49	8.30	102.89
>>	north	415.62	842.31	321.14	1579.1	1397.56	102.99	6.86	3.51	43.47
>>	east	388.67	685.34	362.38	1436.4	1231.57	245.71	16.63	8.37	103.71

*Table **60** : Orientation parameter:: Loads, savings and profits of the aluminium louvered shutter (with control type B).*

Materials and Control types	Orientation	Light. Load kWh	Heat. Load kWh	Cool. Load kWh	Total Load kWh	Consumption kWh	Savings kWh	Savings %	Savings per shutter area €/m²	Maximum Profitable Investment €/m²
Wooden Planar Shutter__Control Type F/ Glazing Parameter										
No shutter	single	331.09	549.94	618.59	1499.62	1149.98				
>>	double	334.64	473.49	592.86	1400.99	1065.90				
>>	triple	338.88	475.15	552.90	1366.93	1054.42				
>>	double Low E	336.95	476.87	565.39	1379.2	1059.65				
>>	double Low E Argon	336.95	456.23	576.18	1369.4	1043.70				
>>	tripleLow E Argon	341.44	485.61	524.55	1351.6	1055.12				
Wooden Shutter	single	422.80	456.94	411.45	1291.19	1058.63	91.35	7.94	3.11	38.56
>>	double	426.89	430.14	418.83	1275.85	1039.13	26.77	2.51	0.91	11.30
>>	triple	430.55	448.18	413.29	1292.03	1058.43	-4.01	-0.38	-0.14	-1.69
>>	double Low E	429.51	452.9	415.05	1297.5	1062.87	-3.22	-0.30	-0.11	-1.36
>>	double Low E Argon	430.39	438.45	418.74	1287.6	1050.90	-7.20	-0.69	-0.25	-3.04
>>	tripleLow E Argon	432.92	472.7	407.12	1312.7	1082.63	-27.51	-2.61	-0.94	-11.61

*Table **61** : Glazing parameter: Loads, savings and profits of the wooden planar shutter (with control type F).*

Materials and Control types	Orientation	Light. Load kWh	Heat. Load kWh	Cool. Load kWh	Total Load kWh	Consumption kWh	Savings kWh	Savings %	Savings per shutter area €/m²	Maximum Profitable Investment €/m²
Pol. Aluminium Coated & Insul. Louvers - Control Type_B / Glazing Parameter										
Alum. Louvers	single	381.48	430.26	336.49	1148.23	958.04	191.94	16.69	6.54	81.02
>>	double	389.28	408.84	354.71	1152.8	952.34	113.55	10.65	3.87	47.93
>>	triple	399.31	429.98	360.04	1189.3	985.83	68.59	6.50	2.34	28.95
>>	double Low E	395.79	435.7	361.67	1193.2	988.74	70.91	6.69	2.42	29.93
>>	double Low E Argon	395.79	423.6	366.89	1186.3	978.91	64.79	6.21	2.21	27.35
>>	tripleLow E Argon	406.11	459.47	363.81	1229.4	1023.76	31.36	2.97	1.07	13.24

*Table **62** : Glazing parameter: Loads, savings and profits of the aluminium louvered shutter (with control type B).*

Appendix A5: Charts of the monitoring

Northern window

Northern window – Shutters are always open

Figure 81: Fluctuation of exterior and interior temperature - when shutters are always open (northern window)

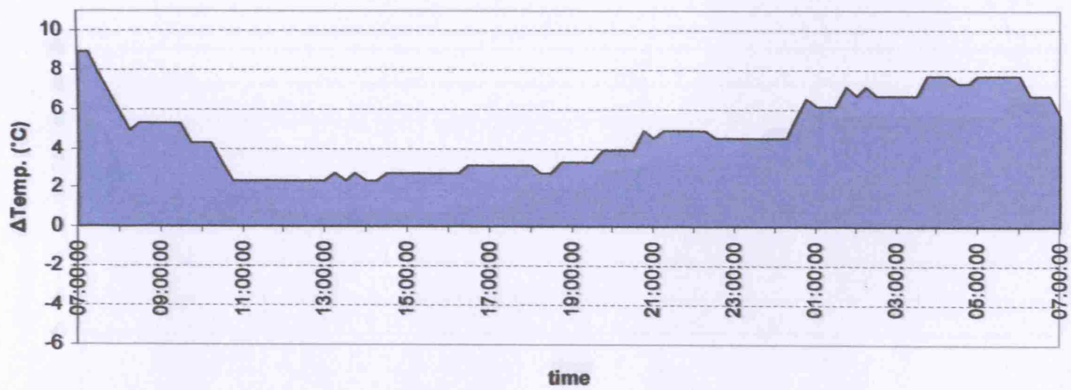


Figure 82: Fluctuation of temperature difference (interior-exterior) - when shutters are always open (northern window)

Northern window – Shutters are always closed

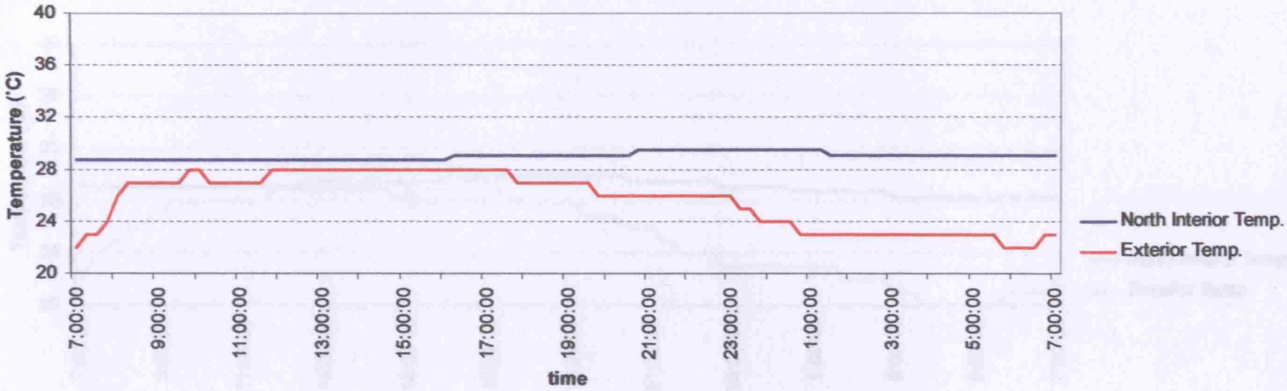


Figure 83: Fluctuation of exterior and interior temperature - when shutters are always closed (northern window)

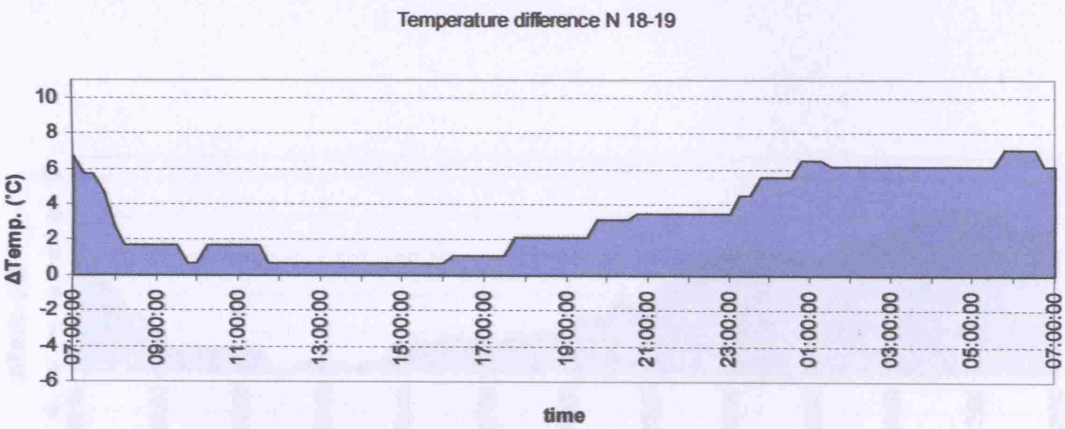


Figure 84: Fluctuation of temperature difference (interior-exterior) - when shutters are always closed (northern window)

Northern window – Shutters are closed during day (7.00-20.00) , open during night (20.00-7.00)

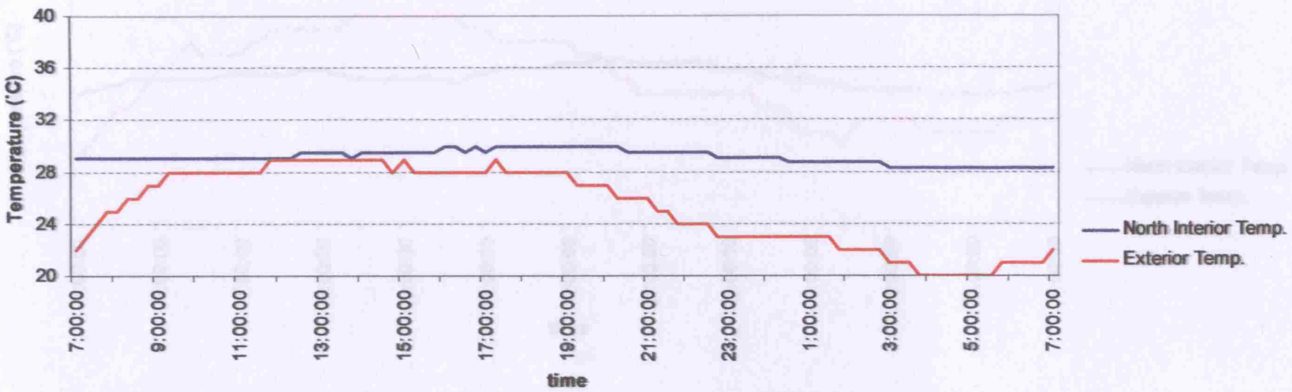


Figure 85: Fluctuation of exterior and interior temperature - when shutters are closed during day, open during night (northern window)

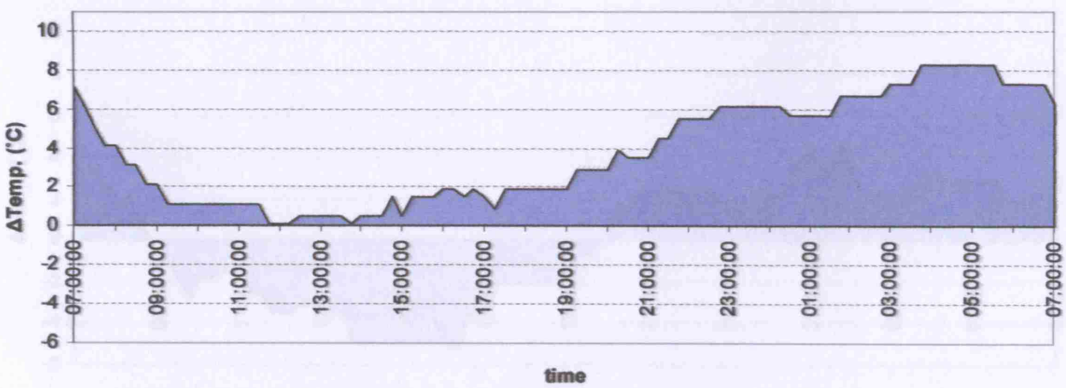


Figure 86: Fluctuation of temperature difference (interior-exterior) - when shutters are closed during day, open during night (northern window)

Northern window – Shutters with aluminium foil closed during day (7.00-20.00), open during night (20.00-7.00)

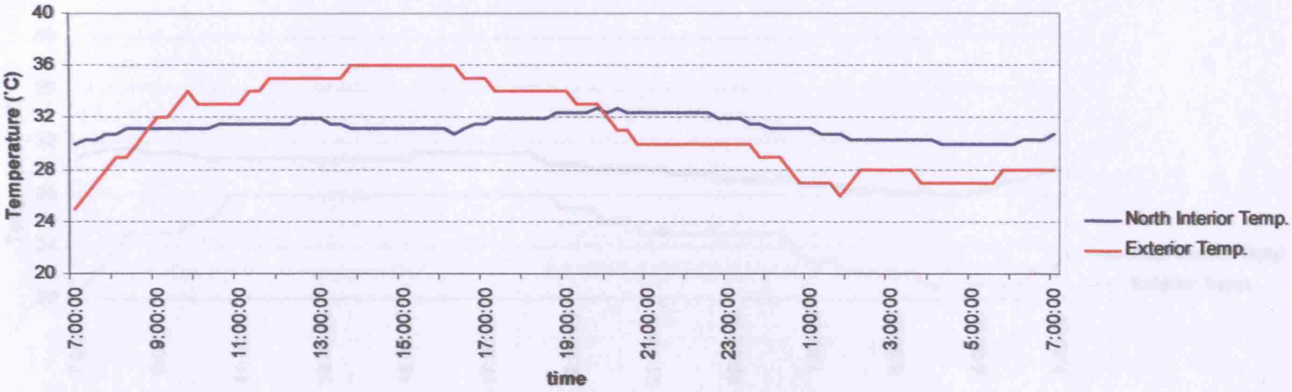


Figure 87: Fluctuation of exterior and interior temperature - when aluminium coated shutters are closed during day, open during night (northern window)

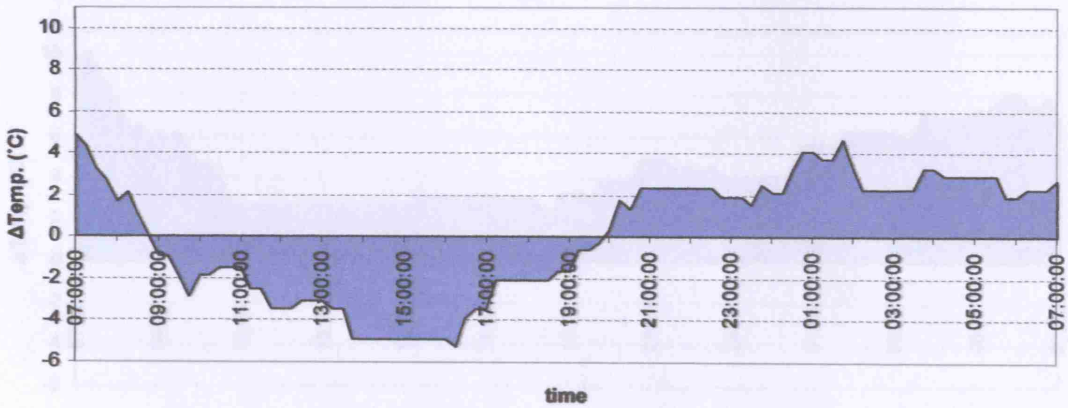


Figure 88: Fluctuation of temperature difference (interior-exterior) - when aluminium coated shutters are closed during day, open during night (northern window)

Eastern window

Eastern window – Shutters are always open

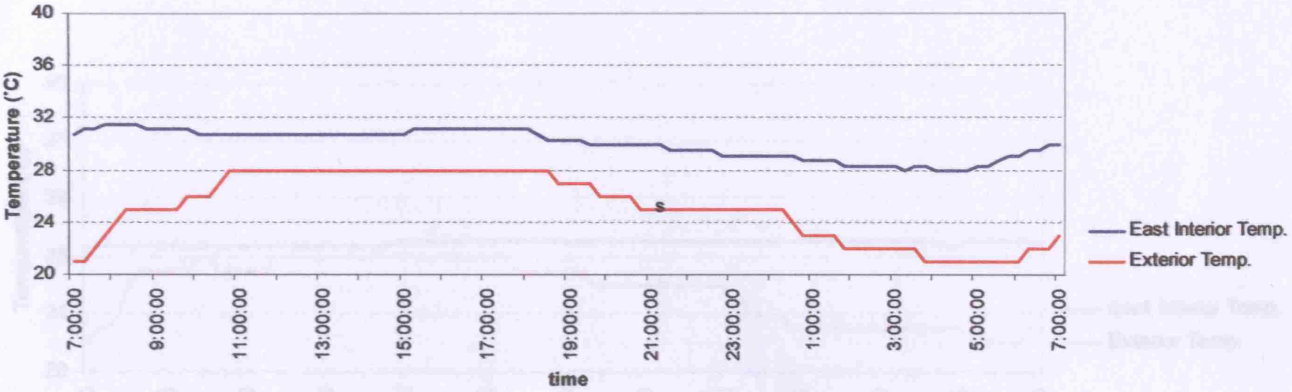


Figure 89: Fluctuation of exterior and interior temperature - when shutters are always open (eastern window)

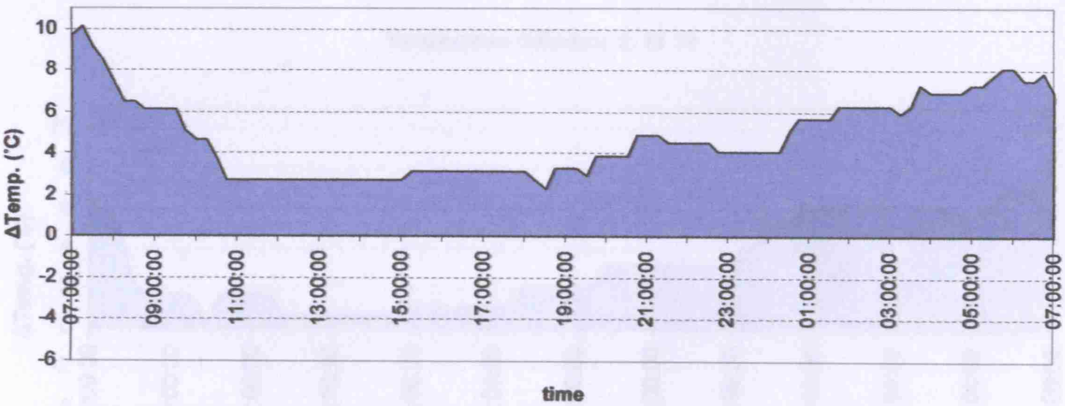


Figure 90: Fluctuation of temperature difference (interior-exterior) - when shutters are always open (eastern window)

Eastern window – Shutters are always closed

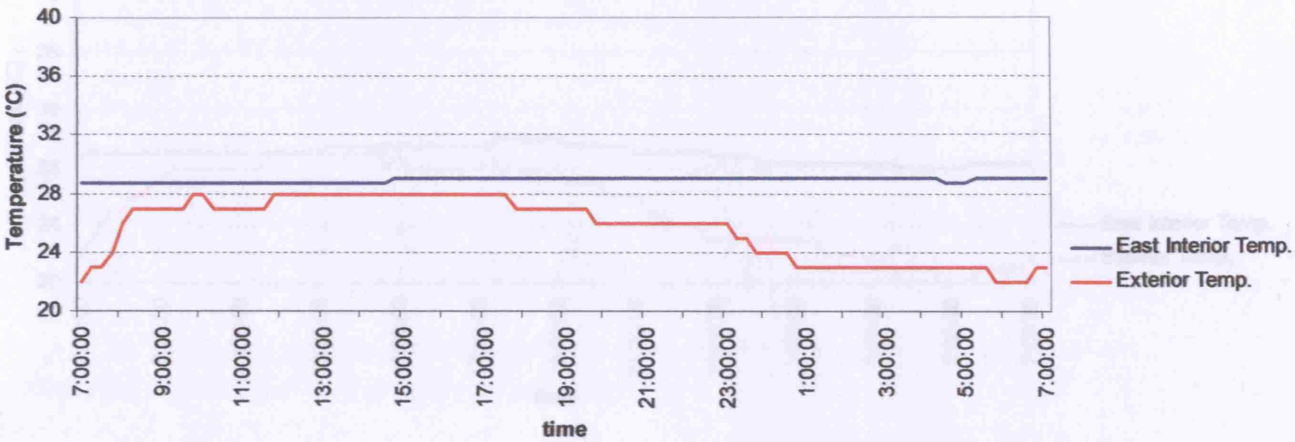


Figure 91: Fluctuation of exterior and interior temperature - when shutters are always closed (eastern window)

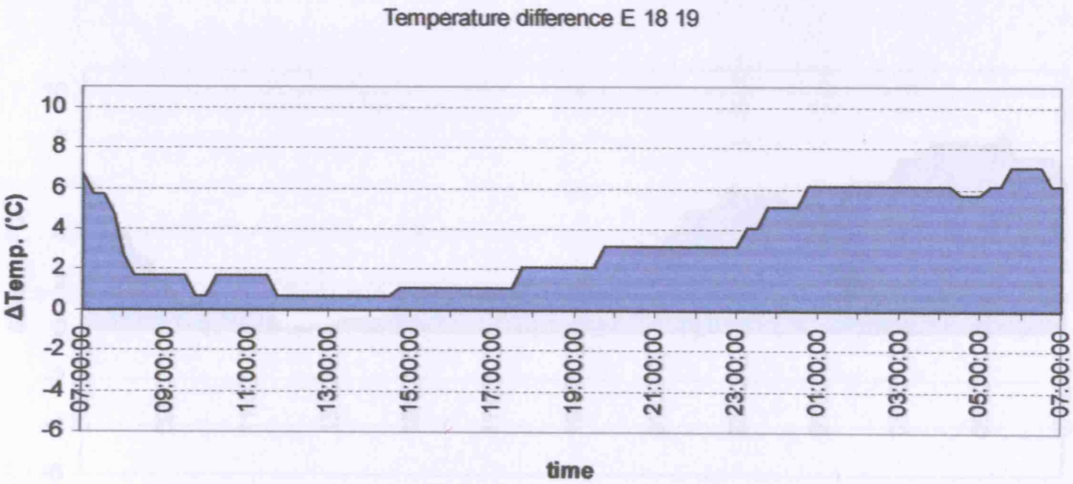


Figure 92: Fluctuation of temperature difference (interior-exterior) - when shutters are always closed (eastern window)

Eastern window –Shutters are closed during day (7.00-20.00) , open during night (20.00-7.00)

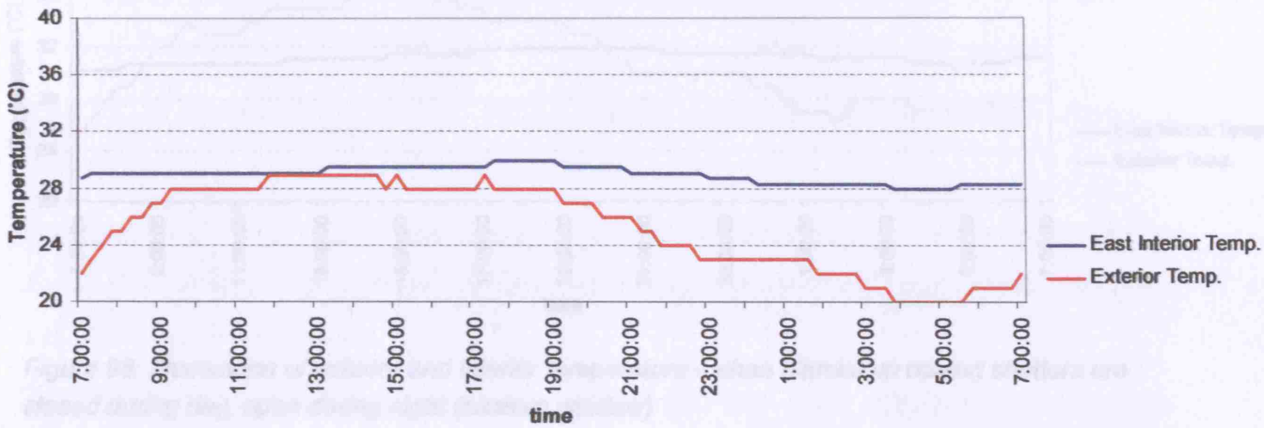


Figure 93: Fluctuation of exterior and interior temperature - when shutters are closed during day, open during night (eastern window)

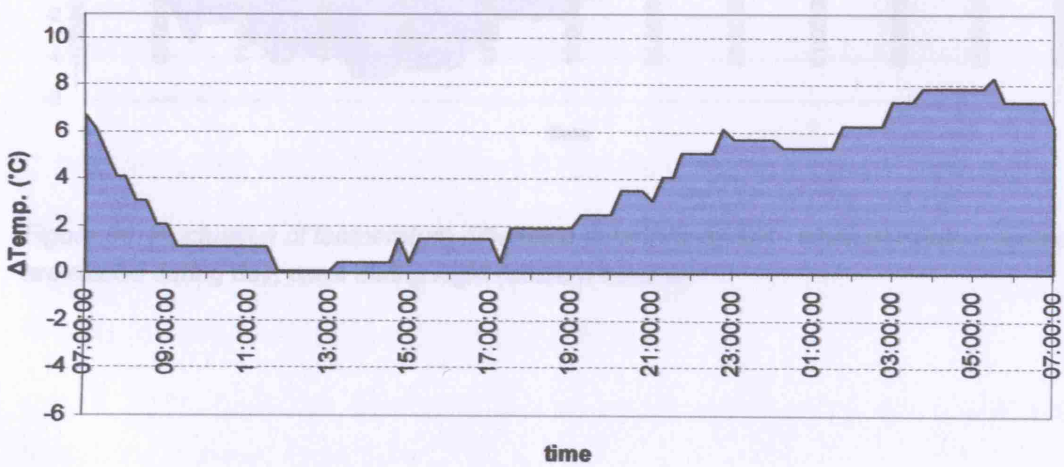


Figure 94: Fluctuation of temperature difference (interior-exterior) - when shutters are closed during day, open during night (eastern window)

Eastern window – Shutters with alumnium foil closed during day (7.00-20.00), open during night (20.00-7.00)

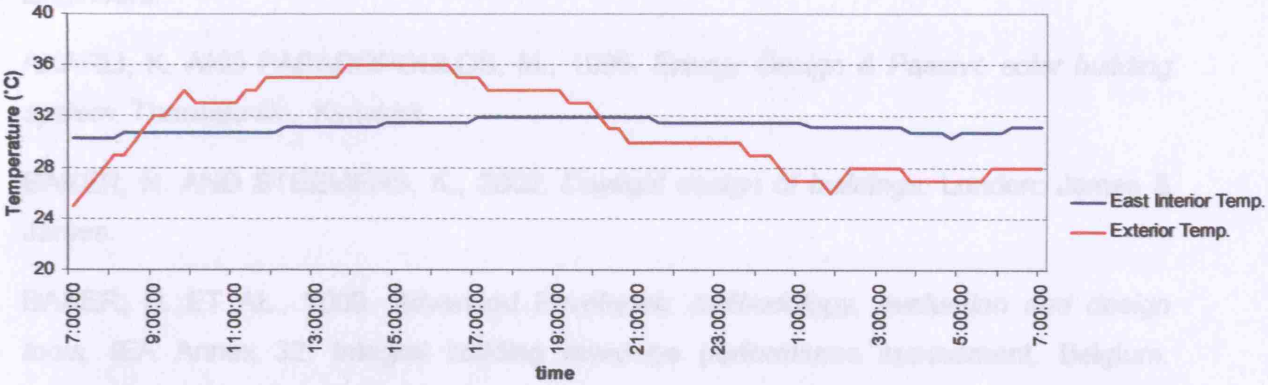


Figure 95: Fluctuation of exterior and interior temperature - when aluminium coated shutters are closed during day, open during night (eastern window)

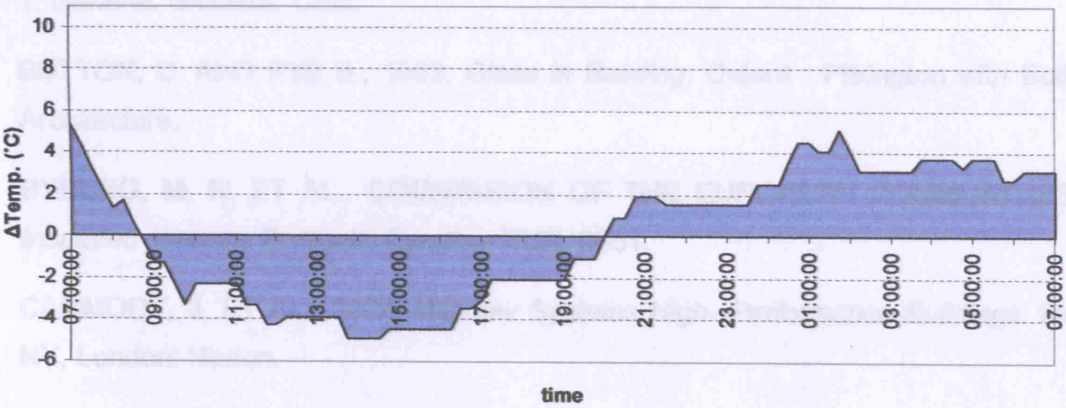


Figure 96: Fluctuation of temperature difference (interior-exterior) - when aluminium coated shutters are closed during day, open during night (eastern window)

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